The application of seismic reflection surveying to the characterisation of aquifer geometry and related active tectonic deformation, North Canterbury.

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By

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Te Whare Wānanga o Waitaha
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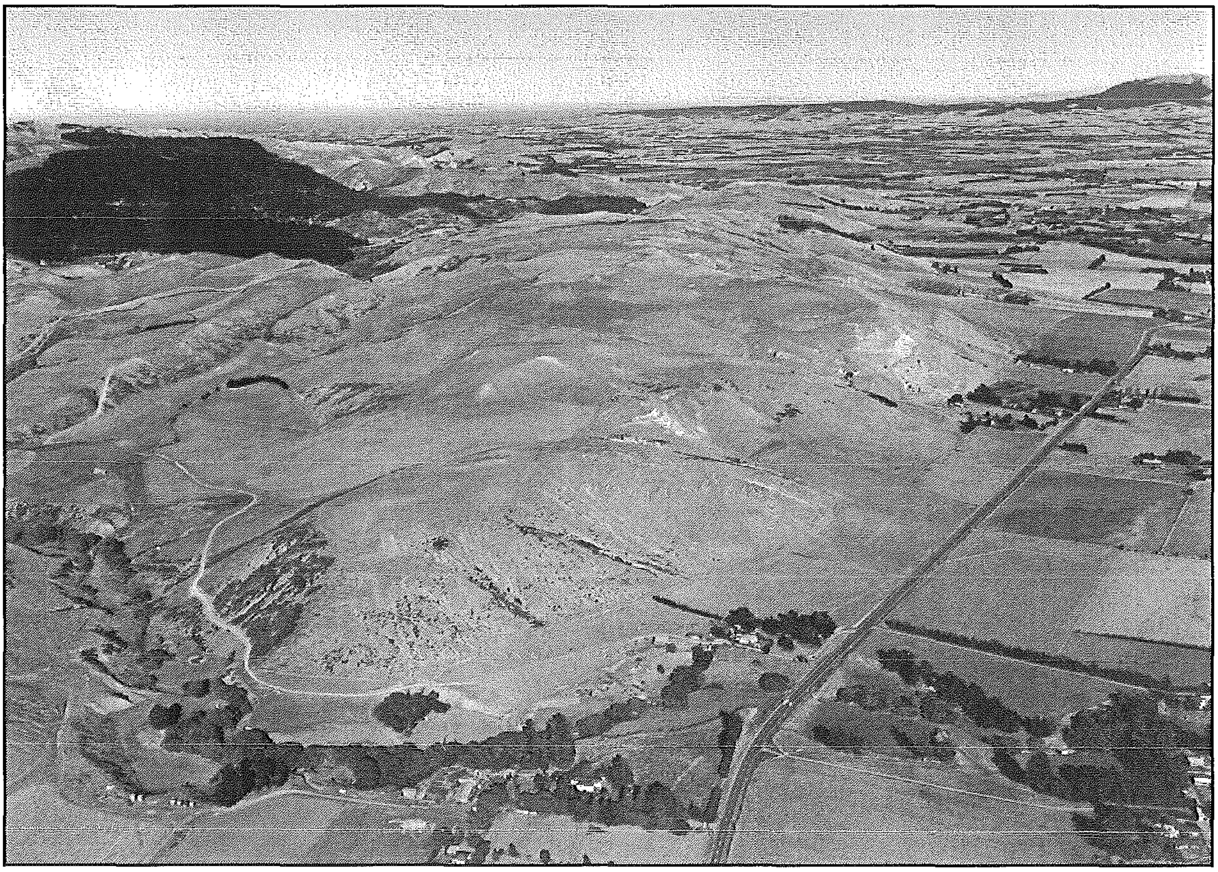

Frontispiece : Oblique aerial photograph of the Omihi Valley North Canterbury (Photograph by Mark Armstrong).

Abstract

Groundwater resources critical to North Canterbury's agriculture, and industrial sustainability and development are predominately located within the Late Quaternary age (0 – 0.78 myr) sediments that underlie, and form the North Canterbury Plains.

The aim of this research is to determine if shallow seismic reflection P-wave surveying is capable of delineating sedimentary architecture related to groundwater resources in the glacio-fluvial and fluvial sediments of the North Canterbury Plains and in particular, if (high porosity/permeability pathways) and aquitard (low permeability) units can be differentiated and so be applied to understanding groundwater resource in the North Canterbury region.

The research was undertaken in three geographic areas in North Canterbury, which represent the main environments for Late Quaternary sedimentary deposition. i) The Omihi Valley a thrust controlled foothill valley setting. ii) The Racecourse Hill-Burnt Hill area which represents a basin-marginal setting close to the emergence of the glacial outwash fans that constitutes the Northwest Canterbury composite aggradation surfaces, and iii) Pines Beach, a more extensively reworked prograding postglacial braidplain with repeated episodes of marine incursion.

Three methodologies have been developed to identify aquifer units in the Late Quaternary sediments of North Canterbury using shallow seismic reflection surveying.

1. Combined structural delineation seismic surveys and borehole logging to define medium scale (10m - 2 km) structures and lithology which affect aquifer and aquitard location and extents.
2. Tailored two and three dimensional shallow seismic reflection surveys to define sedimentary architecture within the larger scale sediment packages delineating high porosity/permeability pathways e.g. paleo-channels in the Omihi Valley and paleo-cut and fill valleys on the Northwestern Canterbury Plains margin.
3. Changes in seismic reflection attributes which directly reflect sediment changes in permeability and porosity such as the decrease in interval velocity with reduced matrix clay/silt content in the Omihi Valley Late Quaternary sediments.

The main research outcome achieved from the 33 km^2 Omihi Valley was the integration of geological/geophysical mapping with lithological borehole logging to develop a groundwater resource model allowing a predictive approach to its exploration and utilization. Structural geometry and styles of deformation of the Valley have also been characterised .

The seismic reflection survey results for Burnt Hill and Racecourse Hill, both basin-margin areas, indicate that seismic surveying can be successfully used to image alluvial and fluvial architecture at scales from 10 m – 1000's m, but with lower lateral (~ 28 m @ 100 m depth) and vertical resolution (4 m) than that of the Omihi Valley surveys. The interpretation of the intra-gravel seismic reflections is complex, and likely only to be possible with three dimensional seismic reflection surveying.

In the third site, only a limited survey of one line was undertaken at Pines Beach (Canterbury Plains/Pegasus Bay junction). This survey indicates that interfingering of reworked finer-grained fluvial sediments and coastal marine sediments can be successfully characterized with

a lateral resolution of < 11 m and vertical resolution of 1.5 m for sediments within the top 50 m.

The research generally demonstrates that shallow seismic reflection P-wave surveying can be extended to the more laterally extensive North Canterbury Plains as a whole, where it is capable of delineating subsurface sedimentary facies, including hydrologically important architecture, down to sub-two metre vertical resolution, in glacio-fluvial, fluvial and shallow marine derived sediments in the 20 – 500 m depth range. The paleo-sedimentary structures successfully delineated in the three field areas include paleo-channels, channel fill, large scale erosional cut-and-fill valleys, floodplain surfaces, and alluvial fans.

It is shown that the aquifer and aquitard contrast in North Canterbury is not characterised by porosity, but by permeability differences (which are also affected by porosity). Aquifers are saturated high porosity/permeable sediments with low silt/clay content while aquitards are saturated units with low permeability which appear (in the Omihi Valley) to be controlled by silt/clay content, but not necessary low porosity.

P-wave seismic reflection surveying is shown to be insensitive to sediment permeability variations, but limited data from the Omihi Valley indicates that seismic P-wave velocities may be sensitive to matrix clay/silt content. If proven elsewhere in the Canterbury Plains region, this may lead to a method of defining aquifer/aquitard geometry directly, without the need to use indirect methods such as paleo-fluvial facies architecture delineation.

This thesis concludes that shallow seismic reflection surveying is capable of characterizing the North Canterbury Plains and foothills valleys sedimentary lithofacies architecture, and also shallow, tectonically-driven structural deformation, when used as part of a multi-faceted programme of investigation. These data can be used to delineate the main groundwater resources. Further research is required to determine if direct aquifer geometry identification is possible by seismic P-wave interval velocity inversions and to increase seismic reflection acquisition speed to allow efficient coverage of large areas.

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A big thanks must go to all the field helpers that I have worked with over the last five years. The seismic sections may just be a single diagram in this thesis, but represent many field days along dusty gravel roads in hot Nor'westers or freezing cold Canterbury winter days. The list of field helpers is too long to list here but a special thanks to the following, Matt Avery, Hamish Gordon, James Grindey, Rob Spiers, and Anekant Wandres.

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Table of Contents

List of Figures

List of Tables

Part I

Introduction

Chapter 1. Introduction

1.1. Introduction and background to thesis:

The Canterbury Plains are located on the East Coast of the South Island, New Zealand, and stretch approximately 180 km north-south and 70 km east-west. The plains are bounded to the west and north by the eastern foothills of the Southern Alps and to the east by the Pacific Ocean. Also to the east of the plains is Banks Peninsula, a significant geographical feature which consists of an extinct volcanic complex (Figure 1.1). The Canterbury Plains are intimately linked to the geologically recent uplift and development of the Southern Alps. The Southern Alps began significant uplift approximately 5 – 6 million years ago (Walcott, 1978). Along with this uplift came an increase in plate boundary convergence, leading to significant gravel detritus being shed off the Southern Alps. Eroded and transported greywacke gravel-dominated sediments from the Southern Alps were deposited forming the Canterbury Plains. Significantly large volumes of sediments have also accumulated in the Plains as a result of the cycle of Pleistocene (1.65 – 0.01 Ma) glaciations. This Southern Alps sediment cycle continues through to the present day as new sediment is conveyed from the Alps out across the Canterbury Plains within large braided rivers. The result of this large scale sediment deposition has been the creation of a productive and intensively farmed area that is home to over 500,000 people with a large agricultural export industry. The ongoing development of this area for agriculture is dependent on the increasing use of groundwater resources contained in the gravel sediments that constitute the Canterbury Plains.

This research targeted specific areas within the North Canterbury Plains and rangefront valleys to evaluate the effectiveness of the seismic reflection method (Figure 1.2). The areas selected are located where active earth deformation is known to be ongoing and previous work, including drilling for groundwater, indicated that the aquifer geometry is more complex than the surface topographic expression indicates. The geophysical research undertaken for this thesis is the first stage of the subsurface information to be incorporated into the existing

Figure 1.1: North Canterbury and Canterbury Plains as seen from space (top is north). Photograph has been corrected for none vertical viewing angle. NASA ID# ISS002-E-5053.

Figure 1.2: Location of field areas on the Canterbury Plains and surrounding foothills. Insert shows location of Canterbury Plains in relation to New Zealand. Topographic and cultural data from the New Zealand Map series NZMS242.

North Canterbury active tectonics and earthquake hazards research programme GIS database (Appendix 8 - Map 1). This combined data repository (geological/geophysical) will allow groundwater resources to be better delineated, managed and rationally exploited in a sustainable manner. It will also resolve several tectono-structural uncertainties currently unaddressed in the existing GIS database.

1.1.1. Thesis Objectives:

This thesis has three main research objectives:

- *To undertake an integrated geological/geophysical survey utilizing detailed seismic reflection profiling of the Omihi Valley in order to develop a groundwater aquifer model and provide rational guidelines for future resource assessment and utilization for sustainable management.*

- *To conduct a pilot investigation, utilising modern seismic reflection equipment, across a selected major fault zone, in order to image its styles of deformation and temporal activity relationships, along the northwest margin of the Canterbury Plains, this in order to evaluate the effectiveness of the technique for future resource assessment; and*

- *To characterise, in several geographic areas, the major sedimentary units and in particular aquifer geometry of the north Canterbury Plains Quaternary sediments, and to assess their extent using geophysical techniques;*

In order to meet these objectives, the thesis is divided into several distinct stages and self-funded field projects, undertaken at different times and geographical locations in the North Canterbury region. This is in order to characterize the contrasting groundwater resource settings with the active plate boundary zone.

1.2. Geographic Setting:

The Canterbury Plains are divided into two morphologically different zones by Banks Peninsula, an extinct early-mid Neogene volcanic complex (Weaver and Smith, 1989). The major rivers crossing the Plains are, from south to north, the Rangitata, Ashburton, Rakaia and the Waimakariri (Figure 1.2). The majority of the seismic surveying and mapping for this thesis was undertaken in the northern Canterbury Plains located north of the Waimakariri River. The main area of research is located in the Omihi Valley located at the edge of the northern Canterbury Plains in the coastal hills between the Mt Cass Range and the Waikari-Scargill Ridge (Figure 1.2). Secondary research areas include several locations in the northwest Canterbury Plains including the Cenozoic outlier of Burnt Hill and Racecourse Hill and a reconnaissance survey was undertaken in north Canterbury on the Pegasus Bay coast at Pines Beach.

1.3. Previous geological mapping and geophysical investigations:

1.3.1. Geological Mapping:

Geological mapping in North Canterbury has been undertaken by many previous workers, key contributions include: Brown et al. (1995), Brown et al. (1988), Field and Brown (1989), Gregg (1964), Sewell et al.(1992), Wilson (1963) and Wilson (1989). Much of this work has been incorporated into the University of Canterbury, North Canterbury GIS database and summarized in Jongens et al. (1999) and is shown in Appendix 8 - Map 1. The following brief lithostratigraphic nomenclature for the Upper Cretaceous and Tertiary Sequence of central and north Canterbury is based on the work of Andrews et al. (1987) and Browne and Field (1985).

Lithostratigraphic nomenclature, North Canterbury

***Mount Somers Volcanics Group** (Cretaceous)*

***Eyre Group** (Characterised by coarse detrital clastics and minor interbedded marine volcanics) (Late Cretaceous-Late Eocene)*

- Monro Conglomerate
- Broken River Formation
- Conway Formation
- Loburn Mudstone
- Waipara Greensand
- Charteris Bay Sandstone
- View Hill Volcanics
- Ashley Mudstone
- Marine Drive Formation
- Homebush Sandstone
- Karetu Sandstone
- Feary Greensand

***Motunau Group** (Clastic and detrital sediments representing a regressive sequence.) (Late Oligocene to Quaternary)*

- Omihi and Waikari Formations
- Mount Brown Formation
- Tokama Siltstone
- Kowai Formation

***Burnt Hill Group** (Characterised by volcaniclastic and flow rocks and some prominent detrital units.) (Mid Tertiary)*

- Wariri Volcaniclastite
- Bradley Sandstone
- Chalk Quarry Sandstone
- Chalk Hill Clay
- Sandpit Tuff
- Bluff Basalt
- Harper Hills Basalt
- Coalgate Bentonite

Miocene volcanics

- Lyttelton-Akaroa Group
- Diamond Harbour Group

1.3.2. Geophysical investigations:

Selected areas of the Canterbury Plains and North Canterbury have also been investigated and mapped using several reconnaissance geophysical methods in an attempt to delineate the basin structure, Cretaceous-Cenozoic stratigraphic cover sequence and the extent of volcanics (Reilly, 1970; Broadbent, 1978; Atkins and Hicks, 1979; Reilly et al., 1979; Ingham, 1997).

The gravity surveys undertaken by Reilly et al. (1979) have a nominal station density of 1 per 10 km^2 across the Canterbury Plains and foothills and an estimated accuracy of 0.1 - 0.5 mgal. This data has been modeled to produce an isopach map of the cover sequence thickness above the Late Paleozoic to Mesozoic age basement, which consists of indurated sandstone and argillite (commonly referred to as greywacke), volcanics, chert and occasional limestone (Hicks, 1989). Modeling indicates that the cover sequence thickness in the four main survey areas of this study varies from 1 km in the Burnt Hill and Racecourse Hill areas to only a few hundred metres in the Omihi Valley and Hawarden Anticline areas. Aeromagnetic surveys were also undertaken in North Canterbury but do not reach any further south than the Ashley River Mouth (Reilly, 1970). The aeromagnetic surveys are of very limited use as they have an interline spacing of approximately 12 km and a flight altitude of 3000 m. This limits their usefulness to the delineation of large scale (>10 km^2) Tertiary volcanics and exposed or unexposed Cretaceous plutonics.

1.3.2.1. Large scale gravity modeling results:

The results of the modeling of the gravity data indicate a north – east to south - west structural grain for the basement geology north of Banks Peninsula. This alignment mirrors that of the Southern Alps foothill orientation, and the strike of the known actively forming anticlines in northeast Canterbury. This basement structural grain appears to be eroded into by a deep feature to the north of Banks Peninsula (Rangiora sub basin) (Hicks, 1989). This feature is mirrored to the south of Banks Peninsula by the similar Rakaia trough (Hicks, 1989). There is uncertainty over the origin of these features. They may be the result of flexure of the crust due to localized loading of the plate adjacent to the volcanic cone. This appears unlikely as Torlesse basement is found outcropping at 300 m above mean sea level within Banks Peninsula. A second possibility is the trapping of the paleo-Waimakariri River to the north of the Banks Peninsula and the paleo-Rakaia River to the south of Banks Peninsula since the initiation of volcanism 11 million year ago (Weaver and Smith, 1989).

1.3.2.2. Hydrocarbon exploration seismic reflection surveys:

Hydrocarbon exploration in North Canterbury has generated several laterally extensive seismic reflection profiles. These have allowed the pre-Quaternary structure and stratigraphic succession to be delineated. The earliest seismic lines were shot by BP-Shell and Todd (BP) companies in 1963 (Appendix 8 - Map 1), (Kirkaldy and Thomas, 1963) and are generally of poor quality with mainly the Mid/Late Quaternary[1] and Kowai horizons imaged (Jongens et al., 1999). The Indo-Pacific Ltd seismic lines (220 km in total length) shot during a survey in 2000 are of much higher quality and show interpretable reflection data to the top of the Mt Somers volcanics (two way travel times of 1.2 - 2 s). Due to the acquisition parameters used during these surveys the shallow part of the section (0 – 300 m) is poorly defined. The low acquisition frequency also meant that features of less than 50 m (thickness) were not imaged.

1.4.Purpose and Scope of the Research:

Over the last 16 years, the Active Tectonics and Earthquake Hazard Research Programme (Department of Geological Sciences, University of Canterbury) has delineated a major zone of active earth deformation involving the northwestern Canterbury Plains and Southern Alps foothills that border the Plains to the west (Pettinga and Armstrong, 1998). Some of the active faults and fault propagated folds have subtle surface expression, with discontinuous preservation of fault scarps, and locally warped terrace surfaces. Beneath the gravels of the Canterbury Plains the bedrock geology is complex, reflecting not only structural displacements, but also a buried paleo-topography. The deposition of aquifers and aquitards is thus inferred to reflect the complex interplay between climatically controlled depositional-erosional cycles (Browne and Naish, 2003), and active earth deformation (Brown and Fisher, 1977; Reilly et al., 1979; Cowan, 1992; Sisson et al., 2001; Estrada, 2003).

A series of recently completed seismic reflection profiles by Indo-Pacific Energy Ltd across the northern Canterbury Plains (Bennett et al., 2000; Campbell et al., 2000), has revealed the presence of extensive active tectonic structures that affect the basin margin, and the complexity of Torlesse basement and Upper Cretaceous-Cenozoic cover stratigraphic relationships (Appendix 8 - Map 1). The Indo-Pacific survey is the first attempt at acquiring high quality seismic profiles across the Canterbury Plains in more than 20 years. The earlier

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[1] The division of the Quaternary into Late Quaternary and Early Quaternary while not universally recognised is used throughout this thesis. The Late Quaternary describes the Lower-Middle Pleistocene and Holocene (0 - 0.78 Ma) and the Early Quaternary represents the Upper Pleistocene (0.78 – 1.8 Ma Pillans (2003)).

profiles acquired in the 1960's are of very poor quality and are interpretable in only the top 1s TWT, (Kirkaldy and Thomas, 1963) (Jongens et al., 1999). Modern seismic equipment, combined with new analytical processing of data using the latest seismic reflection processing software, has revealed that difficulties with respect to velocity inversions and internal reflections can now, in part, be overcome. Furthermore, while the new Indo-Pacific Ltd seismic data are of good quality, it is of limited value for relatively shallow interpretation (less than depths of 500 m) because of the energy source and recording parameters used (Ross, 1999).

The initial aim of this thesis was to undertake a pilot shallow seismic reflection survey at selected localities in order to assess the effectiveness of purpose designed surveys to delineate lithofacies changes within the gravels and, if possible, their depositional, structural and erosional geometry. It was also hoped that the paleo-topography of the Tertiary hydrological "basement" and large-scale structural deformation and dislocation of the aquifer sediments could be delineated. Once the ability of seismic reflection to image shallow structure (< 1 km) in North Canterbury was established the thesis objectives were redefined. It was decided that within the limited time frame of the thesis, characterisation of a large area of the north Canterbury Plains would be impractical and that more multi-faceted surveys in areas of known tectonic activity, likely to control aquifer geometry would be undertaken. These surveys would allow the usefulness of seismic reflection to be quantified in several geologically varied environments and allow several geologic problems to be addressed.

1.5.Reasoning behind the geographical location of the seismic surveys:

The regional tectonic model for the northern Canterbury Plains has been developed over the last 16 years by researchers of the Active Tectonics and Earthquake Hazard Programme at the University of Canterbury, Department of Geological Sciences (Pettinga et al., 2001). Regional and local geologic and geomorphic mapping has been undertaken and the general geological framework for the region is well constrained. The location of the seismic surveys for this thesis is based on the need to compliment and confirm the regional geological model with subsurface data and, at a local level, constrain and quantify the geological detail, especially with respect to individual aquifer units.

Due to time constrains and funding limitations, it is not possible to link the individual surveys in order to produce an all-encompassing structural, hydrogeologic model for the entire area of the Canterbury Plains as part of the overall objective of this thesis.

The individual surveys are aimed at identifying and solving particular research questions, but do not form a continuous interconnected geophysical survey transect across the entire region of the Canterbury Plains. The surveys undertaken investigate three differing structural and sedimentary settings which constitute much of the North Canterbury groundwater resources or where groundwater resources are poorly characterised. The first location was the Omihi Valley. This location offered a range front valley setting at the edge of the Northern Canterbury Plains. The second setting was the Burnt Hill – Racecourse Hill area in northwest Canterbury. This location offered a more representative example of the "average" Canterbury Plains sedimentary and structural setting. The third location, Pines Beach was representative of late Quaternary fluvial-marine transition between the Canterbury Plains and Pegasus Bay shelf.

1.5.1. Omihi Valley:

The Omihi Valley (Figure 1.2) was selected as it offers an active thrust fault controlled basin, which from previous work is known to have accommodated active tectonic deformation of its Quaternary gravel sediments and aquifers (Yousif, 1988; Nicol, 1993; Loris, 2000). The Omihi Valley offers a geologic setting where coeval tectonic deformation and fluvial and alluvial sedimentary aggradation are occurring, and which is broadly well understood and quantified. It also offers a good opportunity to correlate any geophysical surveys with logged borehole data as the valley is undergoing rapid groundwater resource development and boreholes were to be drilled during the time period of this thesis research.

1.5.2. Burnt Hill:

The Burnt Hill area (Figure 1.2) is located within a northeast – southwest trending zone of active faulting and associated earth deformation, parallel to but east of the Porters Pass – Amberley Zone (Cowan, 1992) (Appendix 8 - Map 1). This zone of deformation has been defined by geomorphic mapping and reconnaissance geological mapping, but the zone of deformation is largely mantled by Quaternary gravels, and thus details of the deformation remain poorly defined. Seismic surveying provide an opportunity to delineate the deformation zone at depth, and also image the effect that the active earth deformation has on aquifer geometry across the zone of deformation. The Burnt Hill area also offers a small amount of outcrop information and a scientific exploration well drilled through part of the underlying Tertiary formations (McLennan, 1981).

1.5.3. Racecourse Hill:

Racecourse Hill (Figure 1.2 and Appendix 8 - Map 1) is inferred to be associated with the through-going Hororata fault system and seismic reflection surveying potentially could image the extension of this zone (pers. comm. J.K. Campbell 2002). The Racecourse Hill area also offered the opportunity to correlate the seismic surveys with logged borehole information as additional water wells were again planned for the area within this thesis time frame.

1.5.4. Pines Beach:

The third small survey was undertaken at Pines Beach on the northeast coast of the Canterbury Plains (Figure 1.2). It was designed to quantify the use of shallow seismic reflection methods in an environment that was reworked more extensively; prograding postglacial gravel braidplain environment where repeated episodes of marine incursion has generated permeable (gravel/sand) and less permeable (muds and silts) units on top of each other over the last 700 kyr (Brown, 1998; Browne and Naish, 2003).

1.6.Methodology and Timeline for Research:

The research aims were achieved using a staged approach [2].

1.6.1. Stage one – Acquisition of the necessary seismic equipment:

The initial stage was the acquisition of a shallow seismic system. The system, purchased with funding provided by the University of Canterbury, is designed specifically for shallow seismic reflection work and has reflection cables, geophones elements and seismic source tailored for this requirement. The seismograph chosen has a maximum sampling rate of 0.25 ms which allows frequencies up to 2000 Hz to be recorded without frequency aliasing. Previous surveys indicated that this sample rate would be able to correctly digitize the

[2] Note: The work undertaken for this thesis did not develop in a linear manner as was initially envisioned at the commencement of the study. Several opportunities arose during the first year of this thesis which allowed funding to be obtained for further surveying. The location of these surveys therefore was not fully dictated by initial scientific objectives, but the change was accommodated by a revision of project objectives in order to provide a sustainable funding basis for the seismic reflection surveying and borehole drilling. These changes substantially enhanced the research objectives, and also provided a better focused practical application for the study results.

frequencies expected in the subsurface conditions in Canterbury where the highest seismic reflection wavelet previously recorded was less than 100 Hz (De Vel, 1984; Woodward, 1987; Ross, 1999). The seismograph has a high dynamic range (120 dB) allowing very weak reflection data to be recorded even in the presence of large amplitude ground roll or other noise. The takeout separation chosen for the cables is 6.6 m. This separation allows a geophone group spacing of 0-6 m (+10% tolerance for topographic variation) thus allowing surveys between 0-1000 m in depth to be carried out (Yilmaz and Doherty, 1987). Larger takeout separation would allow deeper surveying to be undertaken, but would increase the cable weights and costs. The geophones selected have a frequency response band of 10 - 300 Hz which includes the expected frequencies encountered in Canterbury sediments. The use of geophone strings consisting of three geophone elements connected in series is to increase the sensitivity of the system to the weak reflection signal. Three seismic sources were developed:

- A hammer and plate system with electrical and mechanical triggering;
- A mini-Sosie source with two 70 kg earth rammers connected in parallel; and
- A pipe gun 12 gauge blank source.

Seismic processing has been undertaken with the Visual Sunt© package, based on the Seismic Unix routines from the Colorado School of Mines (Stockwell, 1997). All seismic interpretation has been undertaken using the 3D Kingdom Suite package©, provided to the Department of Geological Sciences under an educational licence.

1.6.2. Stage two – Environment Canterbury Pilot Project:

With the initial setup of the seismic equipment completed, a series of small surveys were undertaken with support from Environment Canterbury (ECan), the regional government organisation charged with the monitoring and management of groundwater resources in the region.

1.6.2.1. Environment Canterbury seismic survey objectives:

The northwest Canterbury Plains are at present experiencing increasing development as new, water intensive, farming practices are implemented and new rural and rural residential subdivisions are permitted. An understanding of the distribution and geohydrologic characteristics of the underlying aquifer system is required by Environment Canterbury to assist with planning and sustainable management of this important resource.

The ECan pilot project aims are:

- *Evaluating and quantifying the ability of high frequency, high dynamic range seismic systems to penetrate and delineate aquifer structure in the Quaternary fluvial and glacio-fluvial gravel sediments at Burnt Hill and the nearby Eyre River.*

- *Delineating the Cretaceous/Cenozoic basement contact and Quaternary gravel deposits, and so allow the Plio-Pleistocene gravel thickness and its variability to be quantified.*

1.6.3. ECan Project Tasks and Methodology:

The stages within the ECan pilot study included:

- A brief prepared for the project, which integrated the "*Stratigraphic and Structural overview of the onshore Canterbury Basin*" prepared by the University of Canterbury Natural Hazards Research Centre and other relevant survey data, and combined this with the ECan wells database for the proposed study area. This initial summary report was presented to ECan by Finnemore and Pettinga (1999).
- A "simple" hammer and plate, very near surface, reflection and refraction survey was undertaken, to field test and refine equipment and seismic survey procedures, including surveying of source, geophone locations with Global Positioning System (GPS) and laser surveying equipment. The initial survey was across the Burnham age (15-27 kyr) Eyre River deposits and the Ashley/Waimakariri River deposits.
- The collected reflection and refraction survey data was processed, and a workshop presentation was held.
- A repeat of an 800 m section of Indo-Pacific Ltd. line IP98-2 was undertaken to correlate near surface seismic with the deeper Vibroseis sections obtained by Indo-Pacific Ltd, this in order to compare lateral and vertical resolution and preferred acquisition parameters of the two seismic profiles (Appendix 8 - Map 1).
- A 2 km reflection survey in the Burnt Hill area was undertaken to correlate to the ECan and Institute of Geological and Nuclear Sciences (GNS) stratagraphic borehole logs, and surface mapping data.

- Processing of reflection survey data collected during the earlier stages was done and a final report presented with overall results and preliminary interpretations (Finnemore and Pettinga, 2000).

1.6.4. Stage three – A full scale multi-line set of seismic lines to delineate the three dimensional structure and correlate with outcrop and borehole geology:

Once the initial stage two goals had been accomplished the next logical progression was an integrated set of seismic surveys in a location which is undergoing active earth deformation with correlative borehole and outcrop information available. This would allow the seismic stratigraphy to be correlated with known geologic/hydrogeologic stratigraphy and the effect of active tectonic deformation to be investigated.

Funding became available in June 2001 from the Omihi Irrigation Society, a group of farmers interested in developing the groundwater resources in the Omihi Valley in North Canterbury (Figure 1.2). Several logged boreholes were already available from the area and several more wells were scheduled to be drilled during the thesis timeframe in 2002 - 2003. The area is known to be undergoing active earth deformation (e.g Pettinga and Armstrong, 1998; Armstrong, 2000), so met all of the criteria for Stage 3 of the project.

1.6.5. Stage four - Further surveying in selected areas in North Canterbury:

The Omihi Valley and ECan surveys indicated that shallow seismic reflection surveying offers a unique and cost effective method of delineating shallow to medium depth (30 – 500 m) structural geometry and unit lithologies. To evaluate if the method would be successful elsewhere in North Canterbury three further localities were selected, Hawarden, Racecourse Hill and Burnt Hill. Only two of these localities are further dealt with in this thesis (Hawarden has been omitted).

1.6.6. Stage five – The delineation of glacio-fluvial and paleo-fluvial channel structures and other hydrogeologic related structures using very high resolution seismic reflection surveys:

Once the gross geologic structure and lithology was determined several very detailed surveys were undertaken in the Omihi Valley (Part II, Chapter 4). These shallow seismic reflection profiles were to delineate the paleo-geomorphic and paleo-hydrogeologic subsurface units present. The seismic profiles undertaken were located adjacent to a well with a good producing aquifer horizon, and a second borehole with no producing horizon. The aim of the surveys was to delineate the paleo-fluvial channel structure associated with the different horizons, and to evaluate if seismic attributes such as interval velocity and instantaneous amplitude are useful in quantifying porosity and or permeability distributions in the subsurface.

1.7. Overview of the Geology of Canterbury Plains and the North Canterbury Region:

The geological processes that shaped the Canterbury Plains and the North Canterbury Region must be appreciated in order to examine and interpret the geophysical surveys undertaken in this region. The sedimentary and tectonic history of the Canterbury Plains can be divided into three main periods:

1.7.1. Pre-inception of the present plate boundary:

The Late Paleozoic and Mesozoic basement rocks underlying the present Canterbury Plains (and the majority of the northern part of the South Island) are primarily composed of indurated sandstones and argillites (greywacke). The material has been assigned to the Torlesse terrane (Bishop et al., 1985) and is believed to have been formed during convergent margin tectonics during the breakup of the Gondwana super continent 80 myr and maintains the structural grain which reflects this Gondwana margin formation (Bradshaw et al., 1996). The Torlesse terrane is further divided into three subtranes: The southwestern Permian-Triassic Rakaia subterrane, the centrally located Esk Head Melange subterrane and the Upper Jurassic – Lower Cretaceous Pahau subterrane to the east. The Esk Head Melange is an amalgamation of chert, limestone and pillow basalt derived from late Triassic to late Jurassic seamount relics (Silberling et al., 1988). It is predominately comprised of indurated sandstones and argillites which are highly tectonized.

In Mid-Cretaceous times, the New Zealand continental block began to separate and drift away from the Gondwana super continent, accompanied by widespread crustal extension. This extensional regime eventually lead to the opening of the Tasman Sea and the isolation of the New Zealand micro-continent during the early Tertiary. This episode of extension is recorded in the Canterbury region by the onset of Mid-Cretaceous volcanism (Mt Somers Volcanics) and the development of sediment filled fault-bounded grabens such as the Clipper Basin (Wood et al., 1989).

1.7.1.1. Effect of the Volcanism on the Canterbury Plains:

Any discussion of the geologic history of the Canterbury Plains must include the occurrence of volcanism. There have been several major episodes of volcanic activity located within the region of the Canterbury Plains, but volcanic activity ceased before the present plate boundary configuration evolved at the start of the Quaternary. The known history of volcanic activity started with the Mt Somers Volcanics (Weaver and Smith, 1989). These represent the transition from subduction to extension, post the breakup of the Gondwana continent in the Mid-Cretaceous times (~ 100 myr) (Tappenden, 2003) and represent the earliest volcanic deposition in the Central Canterbury area. Mt Somers Volcanics have been recognised in the J.D. George-1 well south of Christchurch (Field and Browne, 1989) and in Indo-Pacific Ltd seismic data (Jongens et al., 1999) covering a large area to South of Banks Peninsula including in the Resolution-1 offshore borehole (Figure 1.3). The Mt Somers volcanics therefore probably represents a major volcanic episode in the Late Cretaceous and were laterally more extensive than previous researchers have supposed.

A second distinct episode of volcanic activity is recognized from limited outcrops in the northwest Canterbury Plains (Weaver and Smith, 1989), and include the View Hill volcanics. These are pillowed tholeiitic basalts and agglomerates of Paleocene to lower Eocene age (65-50 myr) (Andrews et al., 1987). They are located in the Oxford district of North Canterbury and have also been found in the Leeston-1 and offshore boreholes, indicating that volcanic activity may have been widespread during this time. Again, the extent of these volcanics have probably been under-estimated, and are likely to be more geographically extensive than believed by previous researchers (Figure 1.3).

The third episode of volcanic activity occurred during the late Eocene to Oligocene (37-23 myr) and is represented by the Cookson volcanics. These were erupted into a submarine setting, and are alkaline (to transitional alkaline/acidic), tholeiitic basalts. They are localized and poorly understood (Weaver and Smith, 1989).

The final episode of volcanism occurred in the Miocene (5-23 myr) (Weaver and Smith, 1989) and is represented by the Banks Peninsula, Harper Hills Basalt and Oxford Basalt Volcanics. They are of mainly alkaline and basaltic composition. The main centre for Miocene volcanic activity appears to have been the Banks Peninsula, where the Lyttelton and

Akaroa volcanic complex generated at least 1200 km^3 of material during the Miocene. This is likely to be an underestimate as the Lyttelton Volcanics have been imaged on seismic reflection profiles extending 50 km from the present volcanic base. A simple extrapolation of the cone size using this as the maximum extent gives a volcanic volume of >5000 km^2. Whether this represents the real possible extent of the Lyttelton-Akaroa volcanic complex or just a preferential flow direction for the highly mobile lava flows is unknown. To the North of Banks Peninsula no evidence is seen on the seismic lines for Miocene (or Cretaceous) Volcanics, and the Bexley borehole does not penetrate any volcanics (Pettinga et al., 1995). This may indicate that either the volcanic complex is not symmetrical or the Miocene and Cretaceous Volcanics have been eroded to the north.

The volcanics are likely to be impermeable as seen in outcrop on Banks Peninsula and other formations in Canterbury. The Miocene Volcanics underlay the Mt Brown Formation and are likely to represent the geohydrologic "basement" for groundwater resources below the Canterbury Plains. The volcanics offer a good seismic reflector package that can be easily correlated laterally beneath the Canterbury Plains. Miocene volcanics are defined as a strong laterally continuous hummocky/contorted horizontal to sub-horizontal reflector package. At the margins of the Canterbury Plains the volcanics are much closer to the surface and play a significant role in the determining the hydrologic basement and hydrologic pathways. The Miocene volcanics also offer a stratigraphic seismic marker allowing pre- and post-Miocene faulting to be delineated.

1.7.2. The geometry and tectoincs of the present day South Island Plate boundary regime (0 – 2 myr):

The New Zealand micro-continent consists of continental lithosphere that has a majority (>75%) of its mass submerged. Only a small portion of the lithosphere material is emergent, the emergence being a function of the plate boundary oblique collision. The continental lithosphere straddles the active plate boundary between the Australian and Pacific plates. The present tectonic setting is controlled by the interaction between these plates and their differing velocity vectors (Figure 1.4) (Molnar et al., 1975; Walcott, 1978). The interaction of these two plates has given rise to the present oblique-slip trench-trench transform. To the east of the North Island the Pacific plate is subducted beneath the continental lithosphere of the Australian plate, forming the Oligocene-Miocene initiated, east facing Kermadec-Hikurangi Trench. Moving south, the subduction of the Pacific plate beneath the continental lithosphere abates and is replaced by a Pliocene initiated subduction of the Australian plate beneath the continental crust forming the west-facing, Puysegur Trench. This north-south transition from westward thrust to eastward thrust is accommodated by the change in the stress field from thrust in the eastern north island to more strike slip- thrust in the Marlborough area and then eastward thrust in the southern part of the South Island and the Puysegur subduction zone. The complexity of the resulting stress field has resulted in strong zonation of the deformation of the continental crust (Pettinga et al., 1995). The North Islands eastern margin has developed a thrust-faulted system with mainly thrust faults and slope basins backed by a zone of strike-slip shear along the axial ranges. The Northern third of the South Island has developed a broad zone of strike-slip transfer faults, known as the Marlborough Fault System. The lower third of the South Island and Puysegur subduction zone has primarily thrust faulting.

1.7.3. Present-day Active Tectonic Setting of North Canterbury Region:

The North Canterbury region is dominated by the transition from continental subduction to collision which has resulted in crustal shortening and thickening (Reyners and Cowan, 1993) (Figure 1.4). Based on geodetic measurements (Bibby, 1976, 1981; DeMets et al., 1990) 75% of the relative plate motion between the Australian and Pacific Plates is accommodated by deformation along the narrow zone of the Alpine Fault with a further 25% being accommodated in a 150 - 200 km wide zone east of the Alpine Fault, extending into the Canterbury region. The preferred model for this Southern Alps zone of deformation consists of a two-sided deforming wedge (Norris et al., 1990) with possible associated lower crustal delamination (Scherwath et al., 2003). The structural styles of deformation seen within this wedge, indicate a complex pattern of strain partitioning in the upper crust. Based on the contrasting styles of structural deformation and geometry (Pettinga and Armstrong, 1998) have divided the Canterbury Region into eight major structural domains (Figure 1.5). The North Canterbury Region encompasses Domains 3, 4 and 5. The research area for this thesis was located in Domain 4, where the dominate structural character is thrust faulting. The other key site selected for this study is located in the western Canterbury Plains is Domain 5 with thrust/reverse faulting. The dominate structural domain beneath the plains is presently poorly understood but is believed to be dominated by thrust/reverse faulting and fault-propagated folding, both affecting and partially hidden by the Late Quaternary glacial-fluvial cover (Cowan, 1992; Pettinga and Armstrong, 1998; Campbell et al., 2000; Estrada, 2003).

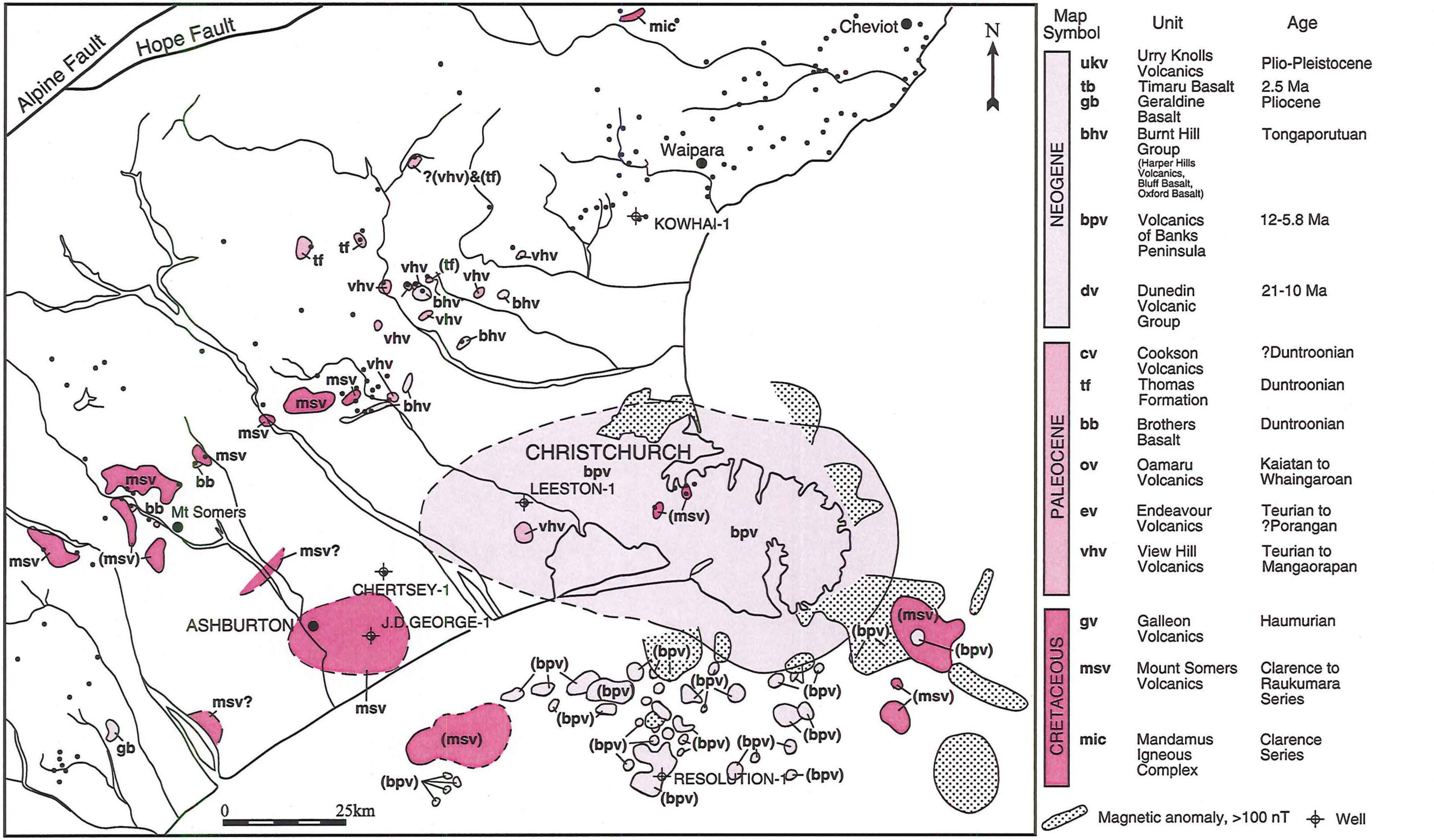


Figure 1.3: Map showing the extent of Late Mesozoic and Cenozoic volcanism in the Canterbury region (modified from Field and Browne 1989). New data derived from Indo-Pacific Seismic lines (Bennet et al 2000).

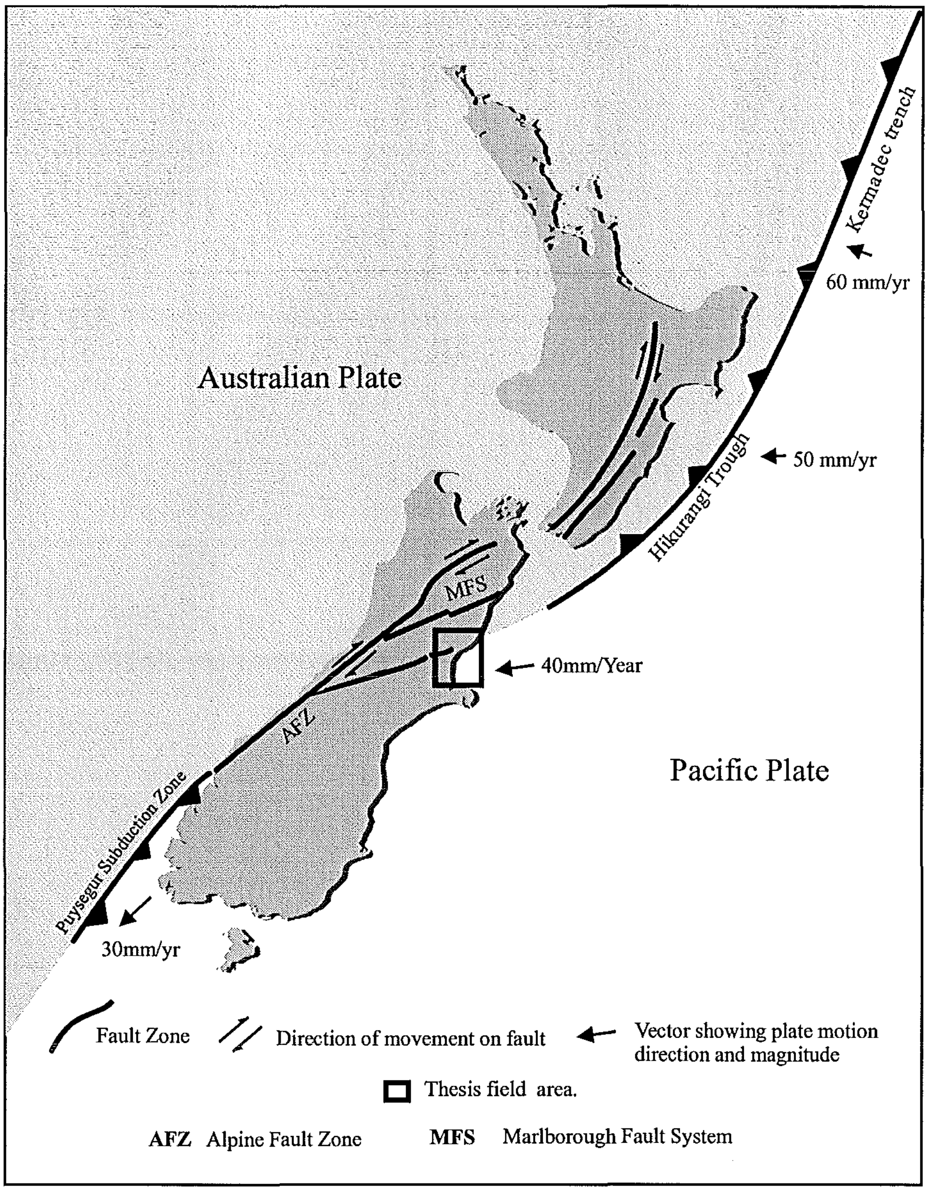


Figure 1.4: Simplified New Zealand plate boundary map and study area location.

1.7.3.1. Domain 5 – Central Canterbury Rangefront Fault Zone:

Continent-continent plate collision across the central South Island has caused deformation forming the Southern Alps and eastern foothills. The geometry of this system of deformation has been described by Norris et al. (1990) as that of a double-sided wedge. This deformation has resulted in the formation of a structural domain were thrust and reverse faulting are the dominant styles of deformation. Domain 5 extents from northwest of Christchurch along the eastern side of the Southern Alps and down to inland of Timaru. The eastern most expression of this style of active thrust faulting in Canterbury is the complex array of faults, folds and associated warping along the west margin of the Canterbury Plains.

1.7.3.2. Domain 4 – North Canterbury fold and fault belt:

This Domain extends from Kaikoura in the north to Amberley in the south and includes a large part of onshore North Canterbury and offshore continental shelf and slope. The thrust faults and fault propagated folds are evolving in response to the oblique plate convergence in the transition zone from subduction at the southern tip of the Hikurangi Trench, to continent-continent collision west of the Chatham Rise. In this domain, the dominant faults are east-dipping reverse/thrust faults associated with asymmetric folding in the hanging-walls, exposing Mesozoic basement greywacke rocks in their core and flanked by Tertiary cover sequence. This faulting results in a topographic expression of alternating anticlinal ridges and synclinal valleys, with the later typically in-filled with Quaternary alluvium and overlain by Tertiary stratigraphy. This structural domain extends to within 5 km of the Hope Fault in North Canterbury, implying that strike-slip deformation here is largely restricted to Domain one to the north, and that the strain partitioning in the upper crust is complex in this region of Canterbury. A further complication is that in this region reactivated Cretaceous faults trending E-ESE are oblique-slip reverse and oblique-slip normal tear faults (Nicol, 1991).

1.7.3.3. Domain 3 – Porters Pass-Amberley Fault Zone (PPAFZ):

The Porters Pass-Amberley Fault Zone has developed in the last 1 Ma and represents the southward migration of the plate boundary zone (Cowan, 1992). The domain is characterised by a system of interrelated E-NE strike-slip faults, oblique thrust and/or reverse faults and associated fault-propagated folds. The total strike slip movement has been estimated to be approximately 2 km (Cowan, 1992).

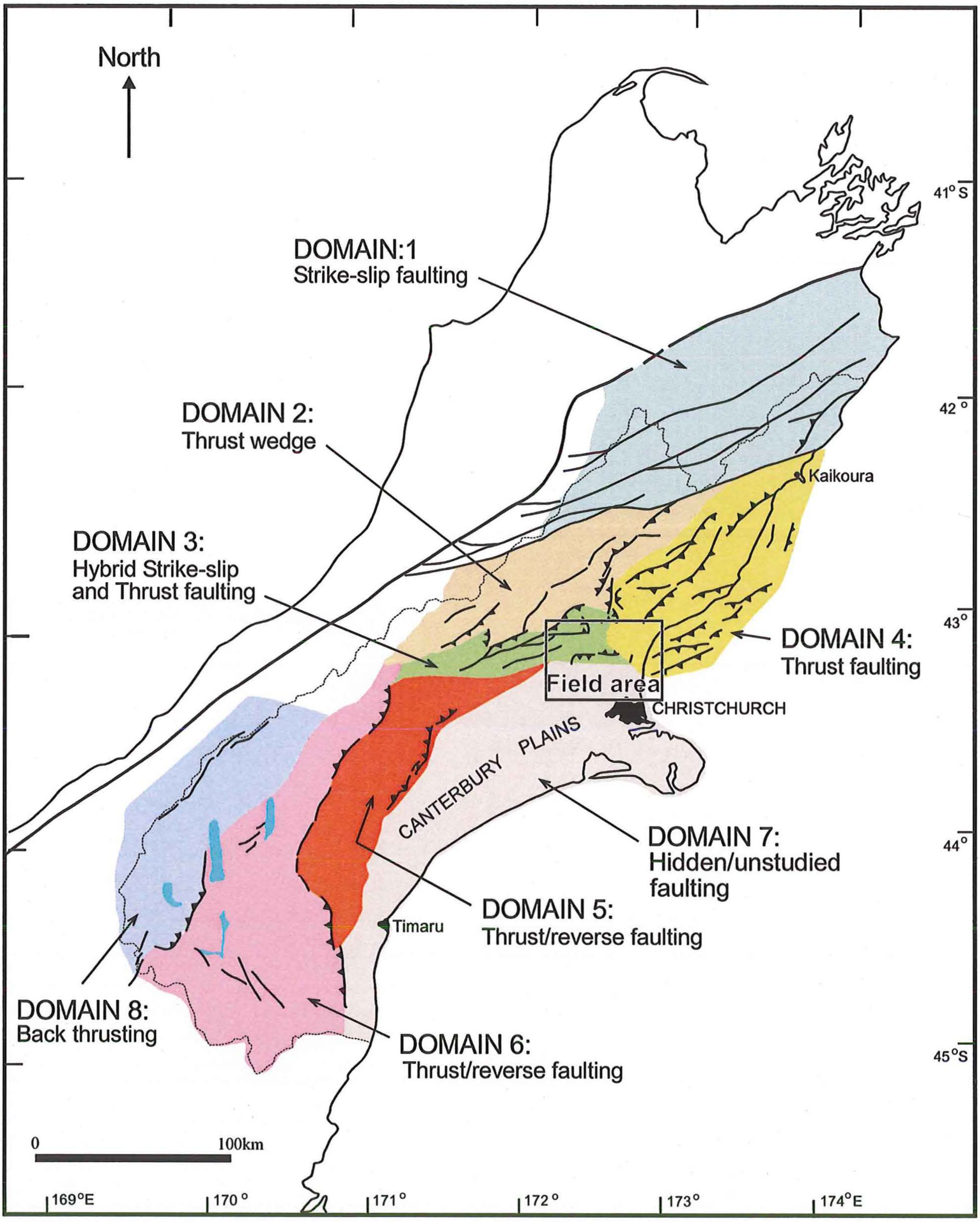


Figure 1.5: Summary map of the structural domains 1 - 8 for the Canterbury region with dominant fault style shown (Pettinga et al, 1998).

1.7.4 Paleoclimate of North Canterbury:

1.7.4.1 Introduction:

While investigations for this study have focused on the effects of active tectonics on aquifer geometry at selected sites in North Canterbury, the effect of large-scale tectonic controls outside the local study areas must also be taken into account, as well as the climatic history of the surrounding mountain regions to the west and northwest, from which much of the sediment has been derived. The main effect of paleoclimate on the aquifers of the Canterbury Plains has been in terms of the control on the volume of sediment supply, as well as the composition (gravel/sand/silt/clay) available for deposition.

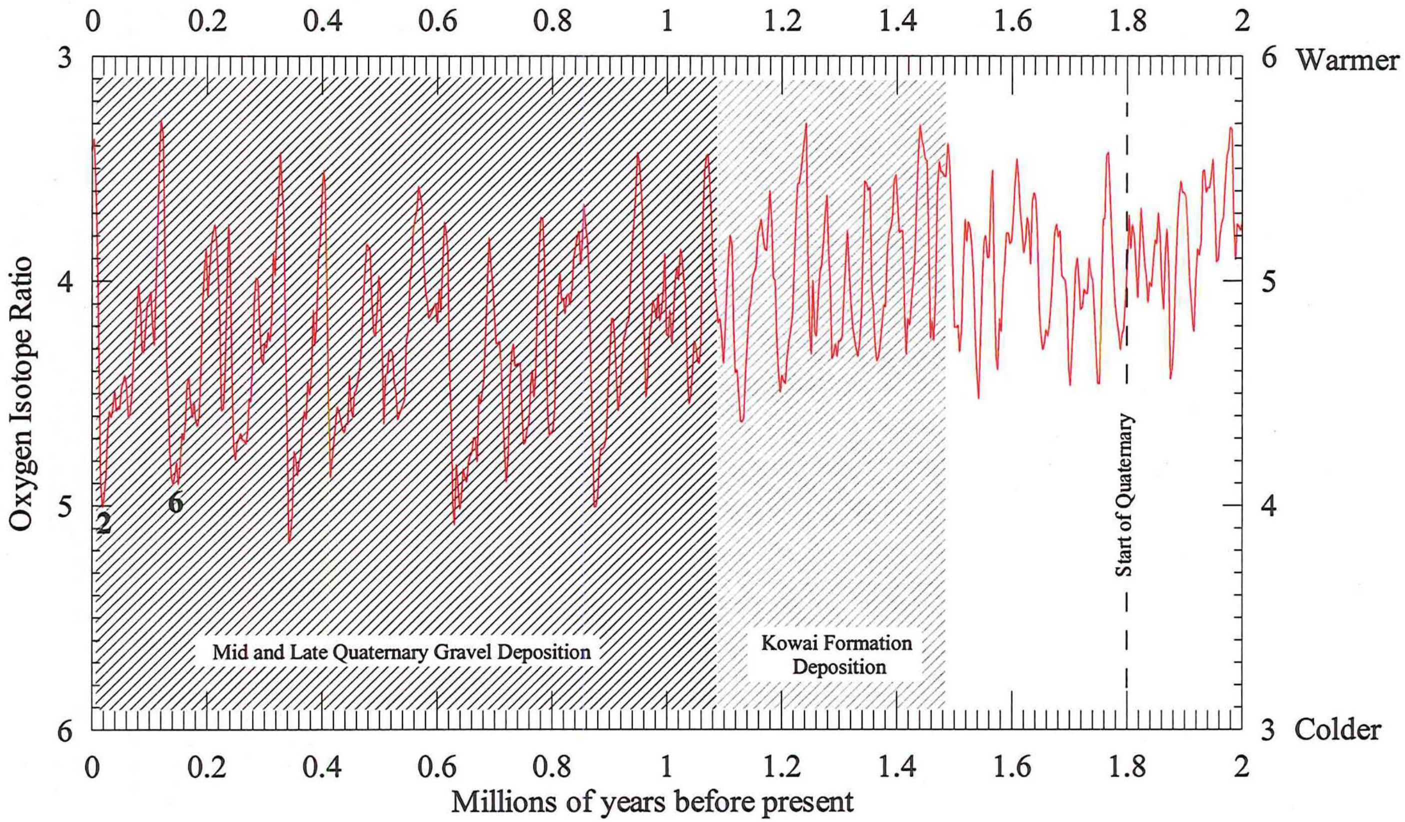
The hydrological basement, for much of North Canterbury is the Kowai Gravel, a clay bound, well weathered Torlesse clast gravel forming the top unit of the Kowai Formation. The Kowai Formation is inferred to have been deposited during the Lower Pleistocene, during the Upper Nukumaruan (1.1 - 1.5 myr) (Gregg, 1959; Browne and Field, 1985). Sedimentary deposition of the Kowai Formation is related to the widening zone of plate boundary deformation forming and extending the Canterbury foothills. By definition, any discussion of the paleo-climate should include the full Quaternary period. The Quaternary period is defined by Williams (1998) starting at 1.8 Ma BP, coinciding with the Olduvai paleomagnetic event. This Plio-Pleistocene boundary for New Zealand may not be the most logical, as glaciation was initiated at approximately 2.4 Ma (Newnham et al., 1999) a date similar to the northern hemispheres rapid build-up of ice cover. A boundary bracketed by the Gauss-Matuyama magnetic reversal in the Lower Pliocene may be the more logical choice to define the onset of glacial-interglacial climate fluctuations in New Zealand.

The deposition of sediment during the Quaternary and Lower Pliocene (0-2.4 Ma BP) in the Northern Canterbury Plains and foothill valleys has been strongly affected by the sediment supply available from the ranges to the northwest and north. This sediment supply has been controlled by the paleo-climatic conditions which directly affected erosion rates, as well as by the ongoing regional tectonic uplift which has controlled the amount of sediment that can be delivered by erosion.

During glacial and post-glacial events, large quantities of clastic sediments are created by the action of glacial processes. For the Canterbury Plains, transportation of these sediments was assisted by fluvial processes and large amounts of materials were transported and subsequently deposited. The exact timing of the transportation of these glacially generated materials is not well known, but is believed to have occurred near the end of the glacial cycle, when higher temperatures resulted in higher flow volumes and greater carrying capacity of the river systems.

The model for the New Zealand paleoclimate during the Quaternary is at present based on global climatic models derived from deep sea core oxygen isotope data (Shackleton and Pisias, 1985; Shackleton and others., 1995b, a), Antarctic and Arctic ice core data (Petit et al., 1999) and Chinese loess deposits (Maher and Thompson, 1994). Limited research has been done locally to improve on the global models being applied to the New Zealand land mass, but at the time of this thesis a detailed New Zealand paleoclimatic model has yet to be fully defined (Suggate and Clapperton, 1990; Pillans, 1991). The Canterbury Plains show dramatic evidence of glacial/interglacial cycles with large morainal terraces visible along many of the major range front valleys, (Suggate and Clapperton, 1990) and glacial loess deposits mantling many areas below 300 m (Shulmeister et al., 2000). Due to the destructive effects of later glacial cycles on early glacial evidence, only three main glacial cycles have been identified and four interglacial events (Suggate and Clapperton, 1990). These events cover a period of approximately 350,000 years. Oxygen isotopic data (O_{18}) from ocean sediment cores are assumed to offer a proxy for the earlier paleoclimatic conditions (older than 350 kyr) for New Zealand (Figure 1.6).

The New Zealand land mass is affected by the Milankovitch orbital fluctuations as are all areas on the Earth. These fluctuations cause variability in the climate over 10 - 100 kyr periods. These fluctuations control the glacial/interglacial cycles. Several high resolution deep-sea core based paleoclimate models have been derived that show this temporal variation in temperature and have been used to correlate benthic water and sea-surface paleo-temperatures with terrestrial climatic events including glacial/interglacial cycles. A complication for the New Zealand paleoclimatic model is the fact that the marine borehole paleo-temperature data is believed to be strongly affected by the variability in ocean paleo-current including the circum-polar Antarctic current. This variability in the current path has the effect of delivering variations in the temperature of seawater to regions over time without any variation in global mean temperature



2 = Last Glacial   6 = Penultimute Glacial

Figure 1.6: Astronomically tuned benthonic oxygen isotope sequence for the Quaternary, based on core data from the boreholes V1930, ODP 677, ODP 846 of the Ocean Drilling Programme. Shackleton, N.J. and Pisias, N.G., 1985, Shackleton et al, 1995a, Shackleton et al, 1995b.

Climatic evidence from terrestrial and marine cores in the New Zealand region indicates that there is broad synchronicity between the global (Northern Hemisphere) and local paleoclimatic history during the Quaternary, (Newnham et al., 1999) but that there may be greater differentiation for short periods, during which changes in, for example, local precipitation patterns and ocean currents may have an important regional effect. Glaciation is believed to have commenced 2.6 - 2.4 Ma but evidence for these early events is fragmentary and poorly dated in New Zealand and only the penultimate (120 kyr) and last glacial (40-20 kyr) cycles can be dated with any certainty.

The absolute dating of moraine and associated outwash deposits in North Canterbury has not been undertaken, and so they have been arbitrarily assigned ages based on the Northern Hemisphere glacial O_{18} stages. Work has been undertaken by Berger et al. (1999) on the loess-paleosol sequences in Canterbury which show periods for loess deposition at 27 kyr, 41 kyr and 70 kyr. The present Canterbury Plains formed from a complex interfingering of glacio/fluvial and alluvial fan deposits derived from the Southern Alps and the Canterbury (eastern) foothills. The formation of the plains has been directly controlled by the available sediment supply, which in turn has been controlled by the climate during the Quaternary (Figure 1.6).

1.8. Development of Seismic Surveying on the Canterbury Plains:

Over the last fifty years, many different geophysical methods have been employed on the Canterbury Plains in order to characterize the near surface geologic and hydrogeologic structure and lithology[3]. Methods include Electrical (TEM, resistivity), GPR and seismic reflection and refraction. Many of the methods have had limited success due to: i) the chemical composition of the gravel clasts and matrix; ii) the technique having a resolution below that necessary to image the hydrogeologic structure; and iii) the limited depth penetration. Some of the earliest geophysical investigations undertaken include seismic reflection and refraction surveys by researchers from Ministry of Works and Development, Central Laboratories and DSIR Geophysics Division (Atkins and Hicks, 1977). These early surveys, the first, by De Vel was undertaken in 1985 in the Kirwee and Rolleston area on the north Canterbury Plains (De Vel, 1984). This work attempted to image the sedimentary

[3] Lithology is used in the general, non strict sense to describe the macroscopic features of a rock type where "rock" includes sediments and other non-consolided materials such as sands, silts and clays and gravels.

stratification structure associated with the aquifers of the Canterbury Plains. Further work was also undertaken in 1985-87 by the DSIR at several locations near Springfield, Orton and Hinds (Woodward, 1987; Woodward and Hicks, 1987). To the north De Vel's results indicated that the lithology and hydrogeology of the northwestern Canterbury Plains limited the usefulness of seismic imaging of the subsurface, due to excessive ground roll, low acoustic impedance contrast between gravel interfaces, and high signal attenuation in the gravels. These results also indicated that the ability to image the subsurface was improved by using mini-Sosie sources over explosive sources. In field areas mainly to the south of De Vel's, the surveys undertaken by Woodward and others met with greater success. Using the mini-Sosie technique they were able to map and follow several producing aquifer units over distances of up to one kilometre.

From this early work it became apparent that the use of seismic reflection surveying, when undertaken using a mini-Sosie source, has the capability to image structures to within 30 m of the ground surface and to depths below 100 m.

In the past several years renewed interest in hydrocarbon exploration in Canterbury resulted in Indo-Pacific Exploration Ltd. undertaking several deep Vibroseis seismic reflection surveys. These surveys were designed to image to a depth of greater than 2000 m and so the seismic survey acquisition parameters were optimised for that purpose. The results of the surveys allowed the base of the Plio-Pleistocene and older units to be clearly imaged, unfortunately they do not image structure within the near-surface (0 – 500 m) Quaternary gravels. Even after careful reprocessing, including detailed velocity and geometry correction, very little detail could be enhanced in the top 200 ms of the data (Ross, 1999). The results indicate that to image structure within the top 200 ms TWT beneath the Canterbury Plains, the reflection survey parameters must be selected specifically to target the Quaternary gravels.

1.9. Organization of Thesis:

This thesis investigates the application of a geophysical method, seismic reflection surveying, to evaluate and delineate groundwater resources and to investigate the effect that ongoing active earth deformation of the Quaternary sedimentary succession beneath the Canterbury Plains has on those groundwater resources. It contains the results of research undertaken in Northwest Canterbury during the years 1999-2003.

The thesis is divided into four main parts and eight appendices.

Part I:

Presented in two chapters (Chapters 1 and 2), the first is a general introduction to the thesis covering project objectives and scope; the previous research on the aquifers of north Canterbury, the geological history of the north Canterbury region and an introduction into the research programme undertaken for this thesis. Chapter Two describes what is known about the aquifers and aquitards of North Canterbury.

Part II:

Divided into two main sections, the first (Chapters 3 - 7) presents the large-scale seismic lines undertaken in the Omihi Valley to delineate the geological structure, and Quaternary stratigraphy beneath the valley floor. The second section (chapter 6) presents the more detailed surveying undertaken to delineate individual aquifer facies and water bearing units.

Part III:

This section (Chapters 8 - 12) describes two geographically diverse sets of seismic reflection surveys undertaken in northwest Canterbury Plains (Burnt Hill and Racecourse Hill) and a North Canterbury coastal survey (Pines Beach).

Part IV:

The final part of the thesis (Chapters 13 - 15) is a summary of investigations undertaken and a synthesis and interpretation of the results from those investigations. Also the limitations of the geophysical methods employed is discussed and possibilities for future geophysical investigations highlighted.

As far is feasible, information which would reduce the readability of the thesis, or is not directly related to the major thrust of the thesis has been assigned to appendices. There are eight appendices including, importantly Appendix 1 includes the geological maps produced and Appendix 8 contains all the seismic sections obtained from the numerous seismic reflection profiles.

Several reports have been completed and submitted to funding organisations during the course of this thesis and also to obtain further funding as research opportunities were recognized and developed. These reports were based on various geographical locations, and aimed at specific targets of the funding providers. The work from most of those reports has been incorporated into this thesis. Specifically, the following reports were produced during the time period of this thesis:

1. *Environment Canterbury Internal Report:*

   A pilot research project proposal to the Canterbury Regional Council: Shallow Seismic Reflection Investigation of Active Fault Control on Aquifer Geometry, NW Canterbury Plains *(Finnemore and Pettinga, 1999).*

2. *Environment Canterbury Internal Report* :

   Shallow seismic reflection study of aquifer geometry in Northwest Canterbury (Finnemore and Pettinga, 2000).

3. *Omihi Irrigation Society Internal Report:*

   Seismic reflection study of Omihi Valley in North Canterbury (Finnemore and Pettinga, 2004).

Chapter 2. Aquifers and Aquitards in North Canterbury

2.1. Introduction:

The aim of this thesis is to delineate the effect that active earth deformation has on aquifer geometry. The purpose of this chapter is to describe the process of aquifer creation and to present the Canterbury Plains and the Omihi Valley aquifer models developed from the thesis research. The active tectonic influence on aquifers and aquitards can be divided into three main components, including:

1. The effect that large-scale active tectonic deformation has on the geological structure of the basins that incorporate the aquifers;
2. The effect of intra-basin deformation (tilting, warping, folding, faulting) on formations/units; and
3. The effect of deformation (tilting, warping, folding, faulting) on the Quaternary sedimentary basin-fill, including the depositional and erosional facies architecture and unit geometries.

This thesis documents the effect that these three processes have on individual aquifer and aquitard geometry and discusses this geometry as appears on seismic reflection survey results for the Omihi Valley and Canterbury Plains region. As a starting point, it is necessary to define what aquifers and aquitards are generally and apply this to the study region within the North Canterbury environment.

2.2. North Canterbury Aquifers and Aquitards:

An *aquifer* is generally defined as a geological unit containing sufficient saturated permeable sediment to yield significant amounts of water; while an *aquitard* is a formation allowing the through flow of water at a much slower rate than an aquifer (Kearey, 1996). A more useful definition for an aquifer in North Canterbury is that an aquifer is a formation or facies which contains sufficiently high porosity and permeability to allow a viable (in financial terms) groundwater production rate. Importantly this formation or facies must be interconnected with the recharge flow paths such that the aquifer will continue to produce once its immediate volume of groundwater has been extracted. The simple assumption that an aquifer is a high porosity unit that is saturated is incorrect in the North Canterbury region. Many of the gravels are clay bound and saturated. Clays have high porosity (33% – 60%) but very low permeability (10^{-9} – 10^{-6} cm/s) (Fetter, 2001). The clay bound gravels therefore tend to have a medium to high porosity (but lower than clean gravels) but low to very low permeability.

By way of example (using porosity values from Fetter (2001):

> A clean gravel has a porosity of 25% - 60%. Assuming that the clay component is infilling the pre-existing pore space and a clay porosity of 33% - 70%, the porosity of a sorted gravel with clay pore space filling is 8 % - 42 %. Therefore the clay in-filled gravel would be expected to have a porosity of $^1/_3$ to ¾ the equivalent clean gravel.

The top half of this range would result in a good aquifer unit if only dependent on porosity, but the hydrologic usefulness is also dependent on two other important parameters, specific yield and permeability.

Specific yield:

The specific yield is the amount of water that drains out in 24 hours divided by the volume of the material. Not all water contained within the pore spaces is free, primarily due to surface tension, cohesion and adhesion, with a percentage of the water thus bound to the particles forming the sediment. This means that the water that may be extracted from the sediment is always less than the total pore water available. A major control on the specific yield of a geological units is grain size. As grain size is reduced so does the specific yield.

Permeability (hydraulic conductivity):

This is a measure of the flow properties through the sediment pore spaces. It is controlled by the geometry and interconnectivity of the sediment pore space and size. Permeability is an extremely complex parameter due to the complex pore geometry, but theoretical and numerical correlation between porosity and permeability has been undertaken by several authors (Nelson, 1994). In most cases porosity can not be directly linked to permeability but it is often systematically realted. Table 2.1 shows the permeability of several sediment types.

Table 2.1, Permeability of selected sediments. Based on Fetter (2001)	
Sediment	Permeability (hydraulic conductivity) cm/s
Well-sorted gravel	$10^{-2} - 1$
Well-sorted sands, glacial outwash	$10^{-3} - 10^{-1}$
Silty sands, fine sands	$10^{-5} - 10^{-3}$
Silt, sandy silts, clayey sands, till	$10^{-6} - 10^{-4}$
Clay	$10^{-9} - 10^{-6}$

The aquifer to aquitard transition is expected to be controlled by the percentage of clay and silt within the pore space through the reduction in permeability and specific yield. Silt reduces permeability by up to three orders of magnitude when compared with well sorted gravels, and clay by a further three orders of magnitude (refer to Table 2.1). Therefore the controlling factor for aquitard formation is *the silt and smaller (interstitial) grain size component* of the gravel. An aquifer must also be saturated if it is going to be exploitable. Therefore aquifers in North Canterbury gravels are:

Gravels with little or no silt or clay filling the inter-clast space (usually Torlesse derived-indurated sandstones gravel clast) with good connection to the main groundwater recharge pathways, and located below the water table.

2.3. Controls on aquifer geometry:

Geologic events, to a large extent, control the qualities of a region. For example, for the North Canterbury Region characteristics of soil type, drainage and mineral resources, including groundwater resources, are to a large extent, a product of geological events and process that occurred in the Quaternary Period in that region. Equally important are geological events and processes that occurred prior to the Quaternary Period. For example, the formation of the source rock that constitutes the majority of the Canterbury Plains gravel clasts (Torlesse-derived) and the emplacement of the Tertiary sequences which underlie the Plains and surrounding foot hills, which may be important in the transportation/recharge of groundwater resources in the overlying gravel sequences. At the present time it is the gravel sequences which are most important with respect to the groundwater resources. The factors controlling the internal geometry of these gravels are four-fold, including:

- Global glacial-interglacial cycles causing changes in climate and sea level resulting in basin/plain wide alteration in aggradational/depositional style. These changes are responsible for thick sedimentary sequences constituting a package of sediments deposited in a similar environment e.g. near shore eustrine/lagoonal deposits and post glacial fluvial braid plain and large scale alluvial fan river deposits.
- Large scale tectonically controlled uplift and subsidence.
- The small-scale channel fill and scour deposits that constitute the individual aquifer units within the gravel sequences. This facies may in total constitute a thick stratigraphic unit, which defines an aquifer stratigraphic sequence.
- Active and recent tectonics which alter the geometry of the deposited gravels and affect groundwater pathways.

It is the fourth controlling variable (active tectonics) that is investigated in this thesis, but this effect is also strongly influenced by the other controlling factors. Active tectonic controls on aquifer geometry are manifested in various ways, including:

- Deformation and faulting of pre-existing stratigraphic units;
- Controlling the geometry of coeval and post-deformation depositional units;
- Altering the local and regional surface fluvial stream gradient profiles and directions, causing changes in post-deformation depositional and aggradation styles;
- Generating both sediment supplies and depositional space;
- Altering the direction of groundwater pathways, causing partitioning/blockage and generation of new/old groundwater pathways.

Actively developing tectonic structures may also have more micro- and macroscopic effects on the sediment fabric within a localized area. (Note: While it is recognized that these macroscopic effects are important they are not further considered in this study). The effect of shaking on sediments by earthquakes is not known but may be locally significant as demonstrated by liquefaction-related features, such as sand bursts and lateral spreading (Nuttli, 1974; Berrill et al., 1994; Christensen and Berrill, 1994). Does the random nature of such vibration tend to sort and align the near-surface unconsolidated sediment during ruptures? Does it tend to cause micro faulting though the sediments effecting the porosity and permeability? The more gradual deformation of sediments in folds will also have an effect on the sediment properties such as the reorientation of clasts directions. The warping of horizontally laid sediments will alter the direction of permeability if the sediment clasts or grains are not randomly deposited in three dimensions.

2.4. Aquifer Models:

This thesis covers two distinct regions of study, the Omihi Valley and the North Canterbury Plains. Although both these areas are located generally in the Canterbury Region, when this thesis refers to the North Canterbury Plains it does not specifically include the surveys and their results from the Omihi Valley research.

2.4.1. North Canterbury Plains Aquifer Model:

The aquifers and aquitards within the thick (> 300 m) gravel/silt/sand underlying the Canterbury Plains are contained within zones of differing hydraulic conductivity (Fetter, 2001). These zones are generated by the fluvial and marine processes that differentiate the sediment clast size, orientation, and matrix components. An understanding of the processes occurring during deposition allows large scale estimates of the geometry, lateral and vertical continuity, and grain size distribution to be made of the aquifers/aquitards. This information can then be used to estimate hydraulic parameters of aquifer units and help in the delineation of zones where groundwater exploration may be more successful.

The aquifers located below the North Canterbury Plains, consist of a highly complex heterogeneous stack of inter-fingered fluvial, glacio-fluvial and shallow marine facies (Brown et al., 1988; Moreton et al., 2002; Browne and Naish, 2003). The present configuration is just the last in a long series of glacial/interglacial environments, which have deposited a stack of variable units (Figure 2.1). The present geometric configuration of alluvial fans and braid plains is believed to be repeated below the present surface as a set of stacked events. The geometry of the sedimentary units within alluvial fans and braid plain deposits is variable depending on the scale of investigation. A large scale overview of the alluvial fan-braid plain can be described as a set of laterally and vertically coalescing alluvial fan deposits and reworked secondary braid plain fans with marine/estuarine events inter-fingering near the coast.

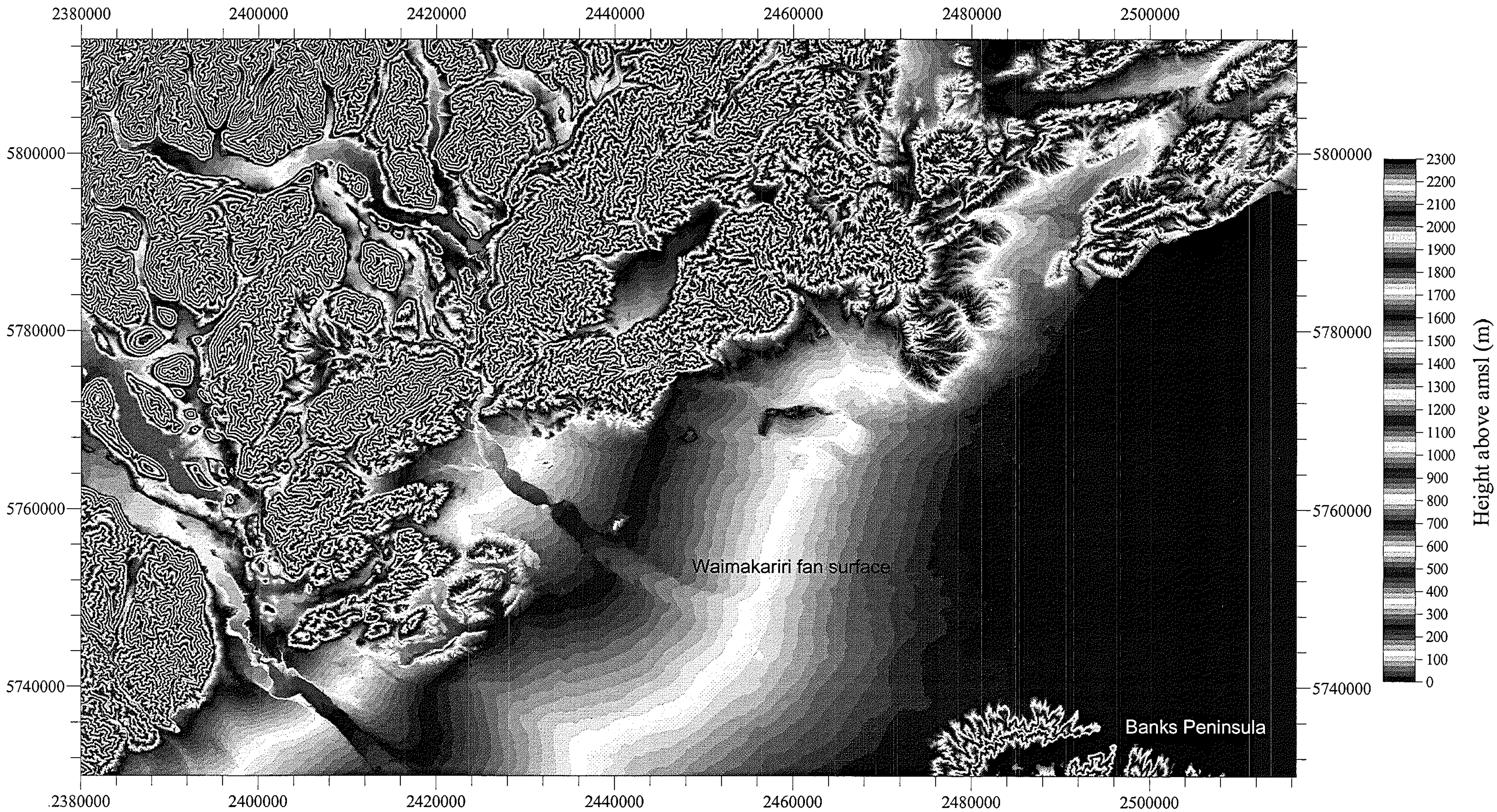


Figure 2.1: A false greyscale map showing the Northern Canterbury Plains and foothills. The map enhances the topographic expression of the alluvial fans that consitute the Canterbury Plains. In the centre of the map the present Waimakariri River fan surface can be clearly seen. Topographic data derived from the New Zealand topographic Map series NZMS 260.

The gravel units that constitute the North Canterbury Plains consist of facies which are both laterally and vertically variable at many different scales. The fan stratigraphy is controlled by the complex interaction of the fan surface and the intersection point (Neton et al., 1994). The intersection point is the point on the surface where the river profile intersects the overall envelope of the fan surface. This intersection point is controlled by tectonics and climate and may result in the fan prograding or retrograding. The stratigraphy is also affected by the lateral migration of the intersection point in normal fan-lobe switching. The general effect of the migration of the intersection point, both laterally and vertically is the development of a set of inter-fingered coarsening-upward or fining upward sequences. The fan progrades during tectonically quiescent periods and retrogrades during basin subsidence. The aquifers beneath the Canterbury Plains are a hydrological facies consisting of clasts of gravel sized (1 - 10 cm) material with minor fines (size?) in the pore space, located in a bulk material consisting of gravels/sands with a high fines content.

2.5. Omihi Valley Aquifer Model:

Valleys located at the margins of the Canterbury Plains have a different sedimentary history to the Plains themselves. An example of such a valley is the Omihi located to the northeast of the Canterbury Plains (Figure 1.2). The present hydrologic regime in the Omihi Valley consists of several streams of the classic meandering model of Miall (1978). The streams have a high sinuosity and low braiding parameter with variable bed load sediment types, ranging from gravel and sand to fines along their course. The streams have low mean flow but during flood events flow rates increase dramatically reaching an estimated 100x greater than normal (A. Munro, per. comm. 2003). These flood events cause deposition overbank fines over a large area. Assuming that the present-day catchment has remained generally similar throughout the Late Quaternary, and that the flow rates have remained similar to within an order of magnitude to the present-day flow rates, it is expected that the Quaternary fill consists of generally meandering stream deposits with a large amount of over bank fines (Miall, 1980). The aquifers in the Omihi Valley are gravel-sized (estimated 10 cm and less) clean material within a generally fines rich environment.

2.6. Sedimentary facies and architectural elements that constitute the aquifer and aquitard units:

The sedimentary depositional environment for the Canterbury Plains and foothills valleys is dominated by a fluvial setting. Glacial moraines and outwash terraces indicate that glacial activity did not extend far beyond the western margin onto the present Plains area, and only the major valley systems, such as the Waimakariri and the Rakaia, were glaciated, foothill valleys such as the Omihi Valley remained unglaciated (Gage, 1958; Wilson, 1989). Glacial events are also likely to have had a more extensive geographical effect due to aeolian loess deposits which were extensive and locally thick (< 15 m) (Liggett and Gregg, 1965). These loess deposits are unlikely to have been thick on the plains themselves, due to their rapid erosion by fluvial processes, but may have developed stratigraphy within the less active foothill valleys and valley slopes. The overall sedimentary history is therefore one of fluvial deposition and incision which resulted in the development of significant architectural features. Globally, the gravel and gravel sand/silt facies deposited by the Canterbury rivers is not as well understood as the more studied sand bed river systems. The gravel bed rivers are a higher energy environment making observations and flume modeling difficult (Miall, 1978). Gravel rivers are in a constant state of dynamic flux, due to external changes such as tectonic and climatic forcing and the effect of seemingly small changes in river geometry which then cause a cascade of changes both upstream and downstream. Relating bed forms to a particular hydraulic environment can be difficult but several broad scale observations have been made.

Many of the elements classified by Miall are possible aquifer units, including CH, GB, SB, DA, LA, HO, and LS (Table 2.2) but from the extensive drilling that has taken place on the Canterbury Plains several conclusions can be drawn with respect to facies identification:

1. During borehole logging it is not possible to distinguish all facies elements from each other.
2. During the drilling and sample recovery process nearly all bedding and sorting information is lost.
3. The recovered samples only allow a simple sediment grainsize distribution to be estimated and a physical description of the clast and matrix material. This leads to several fluvial elements appearing to be similar during drilling, but are in fact derived from very different fluvial processes.

- CH, CF both could contain a high percentage of fines, but are from different depositional processes.
- GB, LA, HO, SG, CH could have a high gravel percentage, but form in very different ways.
- SB, DA, LA, LS, CH all could contain high sand percentages.

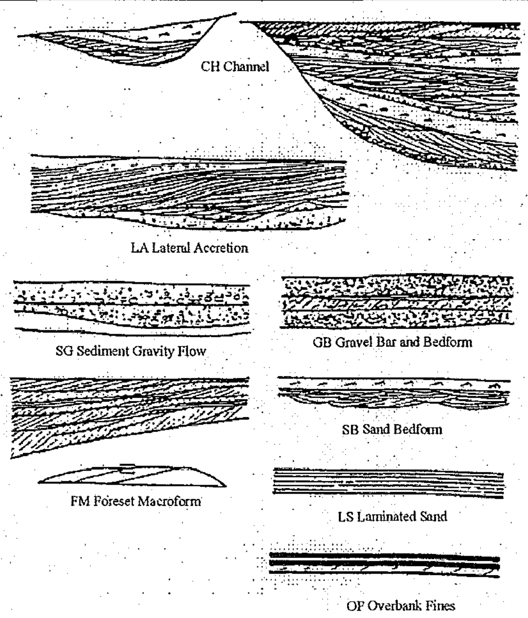
The actual sedimentary elements that constitutes the majority of the Canterbury Plains aquifer units is not known, but is believed to be CH, GB (Moreton et al., 2002). How these aquifer facies, lithologic units and valley-scale aquifer horizons are affected by active tectonics is discussed in more detail in Part IV of this thesis.

2.7.Summary:

The aquifers and aquatards of North Canterbury are controlled by the amount of fines present in the matrix of the gravel, clast-rich sediments. The aquifer units in the Quaternary sediments of the Canterbury Plains are known from drilling to be clast-supported Torlesse gravels or sand units with a matrix of minor fines content. It is believed that the major sedimentary architectural elements which contain aquifers are paleo-channels (CH) and gravel bars (GB) and sand bed forms (SB).

Table 2.2: Fluvial bedform facies classification from Miall (1996).

Element	Symbol	Principal Facies Assemblage	Geometry and Relationships
Channels	CH	All	Finger, lens or sheet; concave-up Erosional base; scale and shape highly variable; internal concave-up 3rd order erosion surfaces common
Gravel bars and bed forms	GB	Gm,Gp,Gt	Lens, blanket; usually tabular bodies; commonly interbedded with SB
Sandy-bedforms	SB	St,Sp,Sh,Sl,Sr,Se,Ss	Lens, sheet, blanket wedge, occurs as channels fills, crevasse splays, minor bars
Downstream-accretion macroform	DA	St,Sp,Sh,Sl,Sr,Se,Ss	Lens resting on flat or channeled base, with convex-up 3rd order internal erosion surfaces and upper 4th order bounding surface
Lateral-accretion macroform	LA	St,Sp,Sh,Sl,Se,Ss less common Gm,Gt,Gp	Wedge, sheet, lobe; characterised by internal lateral-accretion 3rd order surfaces
Scour hollows	HO	Gh,Gt,St,Sl	Scooped-shaped hollow with asymmetric fill
Sediment gravity flows	SG	Gmm,Gmg,Gci,Gcm	Lobe, sheet, typically interbedded with GB
Laminated sand sheet	LS	Sh,Sl; minor Sp, Sr	Sheet, blanket
Overbank fines	FF	Fm,Fl	Thin to thick blankets; commonly interbedded with SB; may fill abandoned channels



Part II

Part II

The geophysical and geological characterisation of the structure and aquifers of the Omihi Valley, North Canterbury.

Format of Part II:

Part II is divided into two main sections. The first section consisting of chapters 3-5, describes the results of research consisting of nine, shallow seismic reflection profiles, and geological and limited geomorphic field mapping undertaken to delineate the structural form and extent of Quaternary age glacio-fluvial and fluvial gravels in the thrust-controlled Omihi Valley, North Canterbury. The section also covers the previous work, geology and aquifers of the Omihi Valley study area. The second section consisting of chapter 6, describes the subsequent, targeted, very high-resolution seismic reflection surveys undertaken to evaluate if seismic reflection surveying can delineate individual paleo-fluvial features and subsurface hydrological parameters in the areas identified. The final chapter, chapter 7 covers the conclusions from all the research undertaken in the Omihi Valley.

Chapter 3. Approach and Purpose

3.1. Introduction:

3.1.1. Rationale:

Agricultural production in North Canterbury is largely controlled by precipitation during the growing season. The precipitation/evaporation balance can be highly variable and the area can be in drought one out of every five years. Currently, land-use in the Omihi Valley is low to medium water-intensive, mainly mixed cattle, deer and sheep farming. The present landowners are interested in developing more water-intensive and productive farming practices such as central pivot irrigation. The surface water resources within the valley are highly seasonal and of limited volume (average of 250 l/s during summer) (Lloyd, 2002). Groundwater is present in the valley as shown by several wildcat wells with yields up to 100 l/s, but producing aquifers are difficult to locate due to their heterogeneous and discontinuous nature. In an effort to reduce the risk, (and therefore the costs) associated with wild cat well drilling, and produce a consistent and sustainable exploration plan, the valley landowners formed the Omihi Irrigation Society. The Society contracted the University of Canterbury to undertake geophysical surveys within the valley, to identify optimum locations for future drilling and to determine the extent of the aquifers if possible. The effectiveness of many "standard" geophysical methods such as ground penetrating radar and resistivity has been shown to be limited in the unconsolidated Quaternary sediments of North Canterbury. As modern seismic reflection techniques had not been trialed in Canterbury, it was therefore decided that the seismic reflection method would be applied, as it has been effective in delineating structure within unconsolidated sediments, similar to those present within the Omihi Valley elsewhere (Rubin et al., 1992; Lanz et al., 1996; Brouwer, 1998; Spitzer, 2001; van der Veen et al., 2001). Part II of the thesis describes the two stages of this exploration program.

3.2. Previous geophysical surveys:

Previous geophysical studies have been undertaken in the Omihi Valley using transient electro-magnetic (T.E.M), ground penetrating radar (G.P.R), gravity and electro-kinetic seismic (E.K.S). These techniques were found to be incapable of defining the valley's sedimentary Quaternary structure or aquifer units (Appendix 4 and 5) (Loris, 2000). The application of these methods is hampered by the composition of the gravels in North Canterbury, which consist of indurated sandstone with feldspar content up to 30% with high fines content (Wandres, 2002). Ground penetrating radar profiling has been attempted in North Canterbury, but the signal is highly attenuated and penetration is too limited for most groundwater studies (<25 m penetration) (Armstrong, 2000). The radar sections are also usually heavily contaminated by diffractions and reflections from cultural features such as fences and power poles. TEM has reduced penetration in the North Canterbury gravels due to the high fines content which reduces resistivity (Armstrong, 2000). The usefulness of TEM is also limited by the small resistivity contrast between clay/silt bound gravels and saturated clean gravels which contain the aquifers. Gravity surveys, while able to define basement topography, (Loris, 2000) are not able to define the Quaternary unconsolidated sedimentary structure and lithology due to the small density difference between the units. EKS shows promise as a possible direct method to identify aquifer and aquitard units but is a new technique and the interpretation of the signal is poorly understood, especially in gravel dominated environments (Appendix 4).

Chapter 4. Geology and Geomorphology of the Omihi Valley

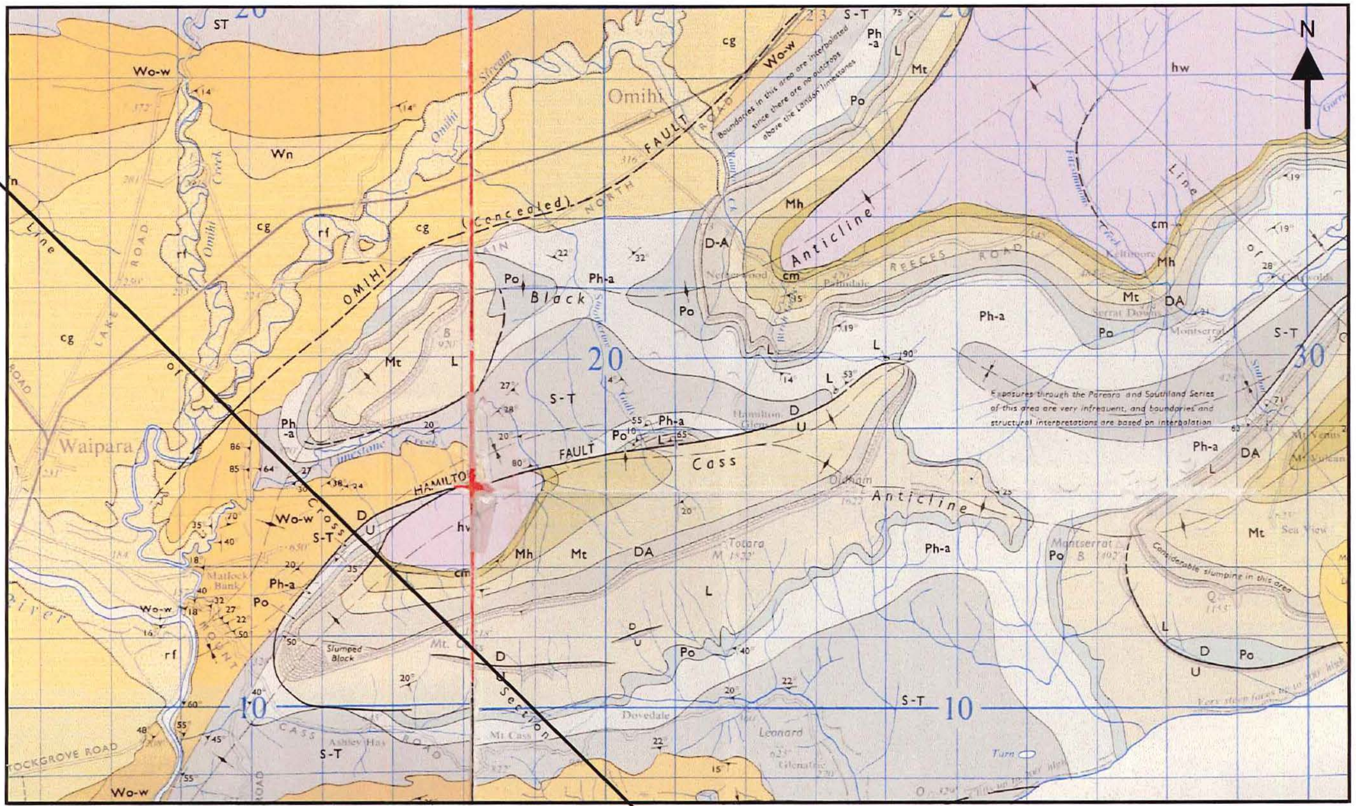
4.1. Introduction:

The purpose of this chapter is to describe the previous research overtaken in the Omihi Valley and place this work in the context of this project. The chapter also describes the mapping undertaken for this project. The main thrust of this project was to investigate the use of shallow seismic reflection surveying, it was not a geologic mapping project which is outside the scope of the study. Mapping work undertaken by Anekant Wandres as part of the Active Tectonics and Earthquake Hazard Research Programme, and was timed to provide an up to date summary of the Omihi Valley geology.

4.1.1. Previous work:

There have been several studies in the last 30 years, which have focused on both the geology and the hydrogeology of the Omihi Valley and surrounding region. The most comprehensive geological publication is Geology of the Waipara Subdivision (Wilson, 1963) published by the New Zealand Geological Survey. Wilson's work provided a synthesis of the geology of the region by compiling all the relevant work up to 1963. Wilson's map for the Omihi Valley is shown in Figure 4.1. Over the last 20 years, the regional tectonic setting and geological structure has been further investigated by Harris (1984), Nicol (1991), Campbell and Nicol (1992), Yousif, (1984), Nicol el al. (1994). A recent compilation of the geological information on the area including unpublished new mapping by Wandres in 2003 has been incorporated into the North Canterbury Geographical Information System (GIS) Department of Geological Sciences of the University of Canterbury.

Omihi Valley section of the Wilson Map 1963



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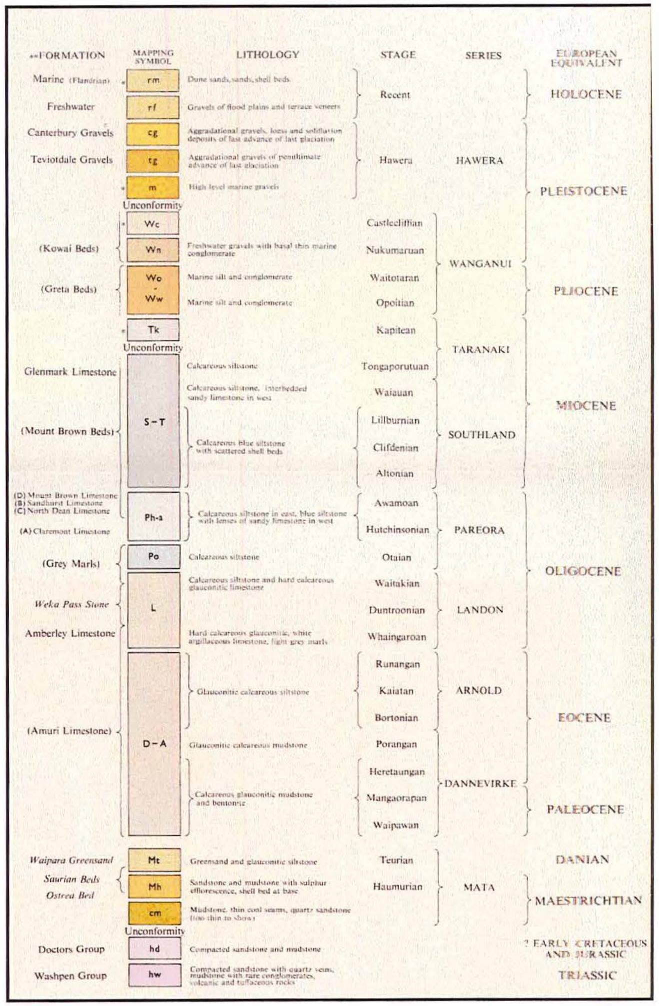

Cross Section B-B'

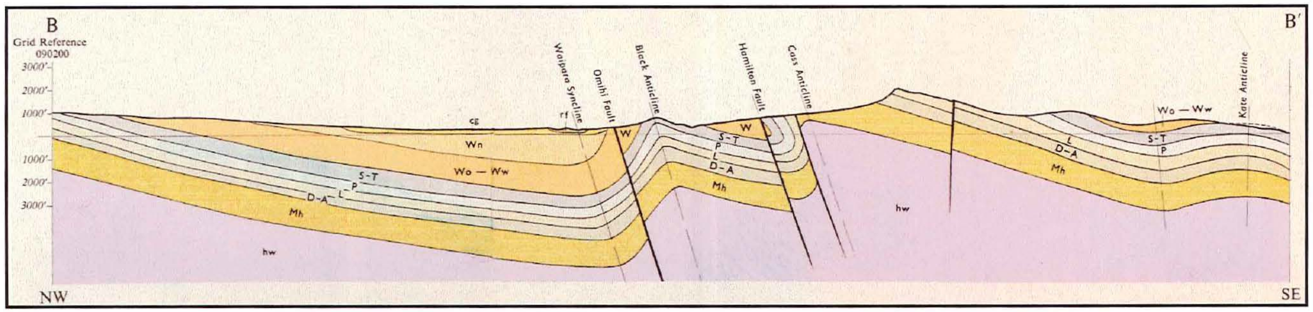

Figure 4.1: Geology of Omihi Valley, part of the map from Waipara Subdivision Bulletin 64, by Wilson (1963).

4.2. Geography and topographic expression of the Omihi Valley:

The Omihi Valley is located at the edge of the northern Canterbury Plains, west of the coastal hills of the Mt Cass Range (Appendix 8 - Map 1). The Omihi Valley has an area of approximately 33 square kilometers, with an average cross-valley width of 2.5 km. The valley floor slopes to the southwest, with a maximum valley floor height (in the northern part of the valley) of 160 m above mean sea level (amsl) and 80 m amsl in the southern portion (Figure 4.2). The peaks to the southeast rise to a maximum of 557 m (Mt Totara) and to the northwest to 442 m (Moores Hill South). The valley and surrounding hills are nearly completely grass-covered with only minor remnants of native forest and some planted exotic forest. In general, the drainage within the valley is from the southeastern valley margin across the valley to the northwest margin, where it combines forming the Omihi Stream, the main surface drainage within the valley and is directed to the southwest. The Omihi Stream is classified as well-meandering, with a high sinuosity index and a mean summer flow rate of $\approx$ 250 l/s (Lloyd, 2002). From personal observation, it appears that sediment transport occurs primarily during times of flood when the Omihi Stream flows increase by an estimated ten-fold. The main topographic features of the valley and surrounding Hills can be seen in Figure 4.2.

4.3. Geology of the Omihi Valley:

4.3.1. Field mapping:

Reconnaissance geological field mapping was undertaken by the author during the collection of geophysical data to allow key stratigraphic and structural elements to be identified and projected into profiles, and so better target further geophysical surveying. Once the structural delineation using seismic reflection surveying was completed, the Omihi Valley was mapped in detail by Anekant Wandres under contract to the Active Tectonics and Earthquake Hazards Research Programme in support of this study. This geological and geophysical database, plus previously collected geological data was then compiled by the author to produce a 12 km by 12 km geological map of the study area and surrounding country (Appendix 8 - Map 2).

4.3.2. Tectonic Setting of the Omihi Valley:

The Omihi Valley is located within the wider zone of active earth deformation caused by the oblique collision of the Australian and Pacific plates. This oblique collision is causing uplift

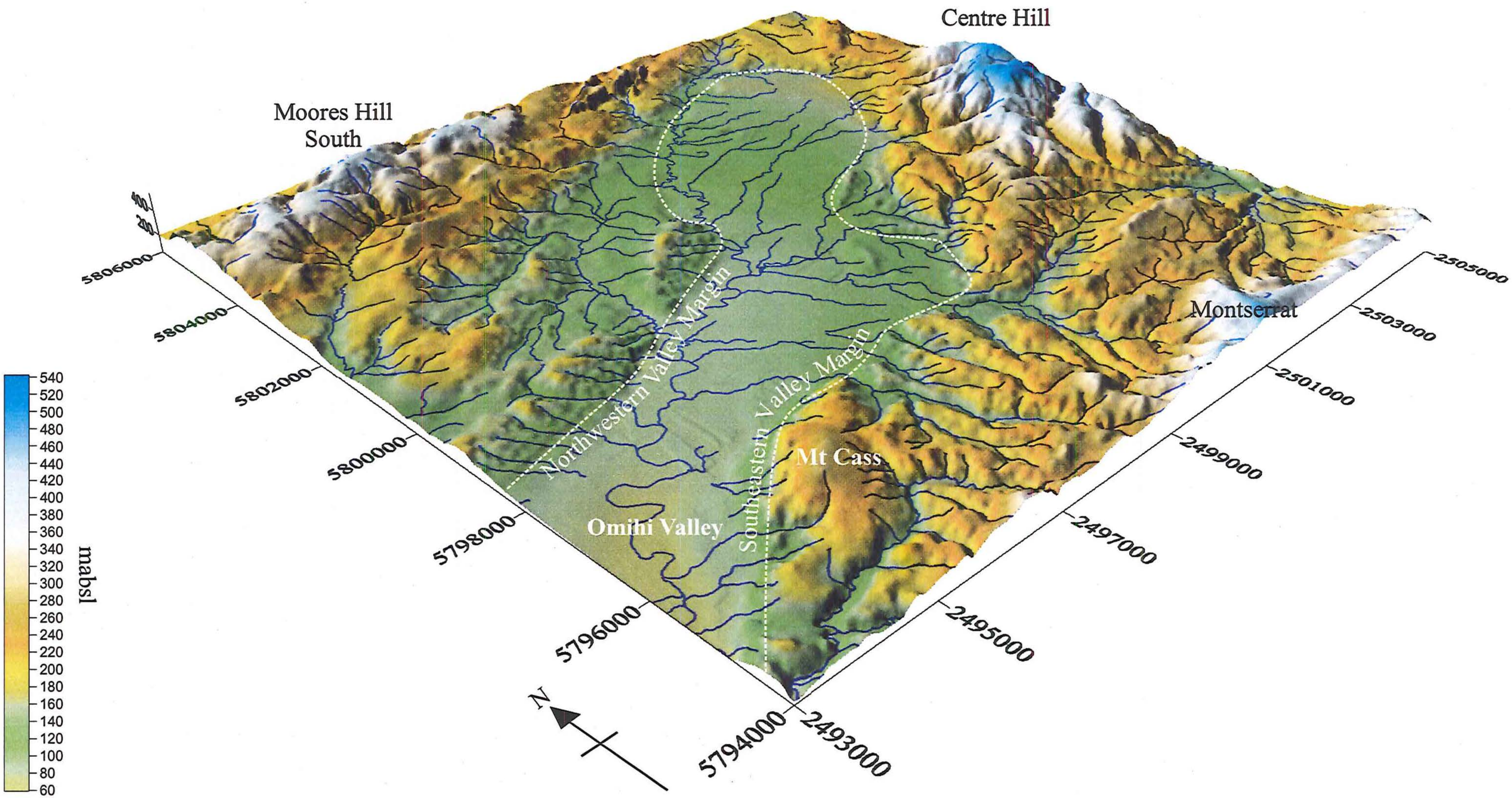

Figure 4.2 : Topographic expression of the Omihi Valley shown with a 2:1 vertical exaggeration. Grid is based on the New Zealand Map Grid NZMG260. Valley drainage is shown in blue.

and tilting of the overriding Pacific plate forming the Southern Alps and associated north Canterbury foothills (Figure 1.2).

The two major structures accommodating the deformation produced along this 150 km wide plate boundary zone are the Alpine Fault Zone (AFZ) and the Marlborough Fault System (MFS). The Alpine Fault is a major oblique strike-slip fault, extending the length of the South Island; while the MFS is a zone of right-lateral, strike-slip, transfer faults, located in northern South Island, and splaying off the Alpine fault to the northeast, linking in turn to the Hikurangi Subduction margin (Figure 1.4). The Omihi Valley is located in the zone of thrust driven deformation, southeast of the MFS, (Figure 1.4) (Pettinga et al., 2001). Folding and faulting in North Canterbury is reflected in the topography with faults being associated with fault propagated asymmetric folds (Yousif, 1988; Nicol et al., 1994; Litchfield, 1995). This has resulted in the formation of a fold and thrust belt (extending up to 20 km offshore) (Barnes, 1993; Barnes, 1995) where up to 12-15% northwest-southeast shortening has occurred during the Pleistocene (Nicol et al., 1994; Cowan et al., 1996).

4.3.3. Initial structural model of the Omihi Valley:

Prior to any seismic reflection surveying or new geologic mapping for this project, an initial structural model for the valley was formulated using previously available information. The model is shown in Figure 4.3. Wilson's model for the valley was updated to account for more recent information on the tectonic regime in North Canterbury (see summary in Pettinga et al. (2001)), and also new research on fault plane dynamics and architecture in a transpressional tectonic environment (Jamison, 1991). It was expected that the present Omihi Valley tectonic structure would consist of a complex series of fault driven structures accommodating the near surface upper crustal strain, including imbricate faulting, back thrusts and other strike/slip related features. Previous mapping had shown that the structure of the valley is that of an asymmetric syncline, with the southeast dipping Omihi fault (concealed) on the southeastern valley margin. The structural model for the valley was visualized to include complex imbricate faulting in the footwall, with possible back thrusts and minor fault splays in the valley subsurface as seen elsewhere in north Canterbury (Litchfield et al., 2003).

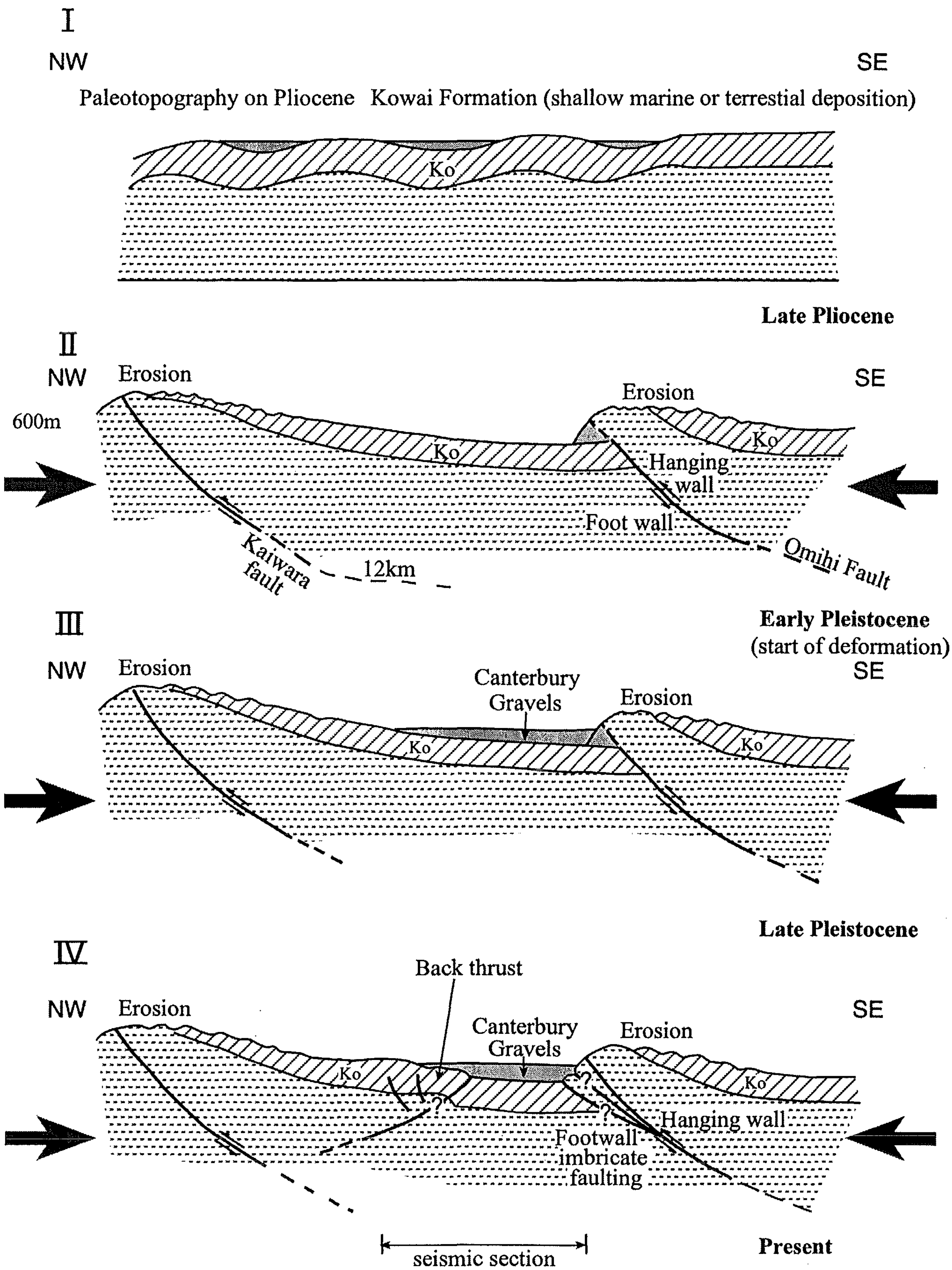

Figure 4.3: Omihi Valley structural model (after Pettinga).

4.3.4. Stratigraphy:

The stratigraphic succession and lithostratigraphic nomenclature for the valley and surrounding area, is defined by Wilson (1963), Browne and Field (1985), Nicol (1991), Yousif (1988) is:

Torlesse Supergroup (95-170 myr)

Within the Omihi Valley and surrounding area, the Torlesse outcrops represent the basement rock. It consists of Mesozoic age indurated sandstone or mudstone (argillite) and is known colloquially as "greywacke".

Amuri Limestone Formation (26-37 myr)

This formation is a Oligocene aged moderately strong, fine grained, dense, distinctive white limestone (calcilutite) and marl.

Weka Pass Stone (26-37 myr)

This Late Oligocene unit is a fine sandy limestone, cream in colour, and is part of the Omihi Formation (glauconitic calcareous sandstone).

Mt Brown Formation (11-24 myr)

This Miocene formation is very diverse, consisting of interbeded, hard sandy limestones, calcareous sandstone and siltstone.

Kowai Formation[7] and Gravels (1-2 myr)

The Kowai Formation consists of Pleistocene age moderately indurated fine sandstone and blue siltstone with intermittent layers and lenses of rounded pebbles, overlain by a thick sequence of fluvial gravels (Kowai Gravel member, see below). The thickness of the Kowai Formation is variable (Wilson, 1963) but is estimated to range from 580-650 m (Browne and Field, 1985).

Kowai Gravels

The name Kowai Gravels usually refers to the top unit of the Kowai Formation (Browne and Field, 1985). The Kowai Gravels are river deposits with possible marine phases. They are composed of weathered, limonite stained gravel consisting of predominantly greywacke and argillite clasts, with minor Tertiary derived clasts, in a silty clay matrix. Determination of the age of these gravels and associated Kowai Formation is problematic, but their stratigraphic position is clear.

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[7] (Browne and Field, 1985)

Teviotdale Gravels (120 kyr.-200 kyr)

The Teviotdale Gravels are composed of predominantly greywacke and argillite clasts, with minor Tertiary derived clasts, in a silty clay matrix. The gravels have a creamy brown leached colour with yellow-brown fine sand and silty matrix (Wilson, 1963). The Teviotdale Gravels lie unconformably on the older Kowai Formation and have an estimated thickness of 100 m (Wilson, 1963). It is believed to have been deposited during the penultimate glaciation.

Canterbury or Omihi Gravels (1 kyr – 80 kyr)

The Canterbury Gravels are composed of greywacke clasts with a lower percentage of silt and clay in their matrix than the Teviotdale Gravels, which they unconformably overlay. The Canterbury Gravels are predomininantly clast supported (Wilson, 1963). The Canterbury-Omihi Gravels are inferred to have been laid down during the last major period of glaciation, approximately 10-80,000 yrs (Otira Glaciation) (Wilson, 1963).

Modern River Alluvium (< 1 kyr)

This alluvium consists of gravels, sand and silts deposited by the present courses of the streams in the valley. The present streams are incising into the older material causing most of the modern river alluvium to be deposited below the older valley floor surface. The gravels consist of mainly Torlesse (greywacke) derived indurated sandstone clasts, but also a high percentage of limestone clasts are recorded at several localities.

There are also several other formations present in the area. They are not of interest in respect to groundwater, as they are beyond the depth of drilling that is likely to be undertaken in the foreseeable future and/or they outcrop some distance from the main axis of the valley. These stratigraphic units are shown in the stratigraphic column shown in Figure 4.4, but are not further described here.

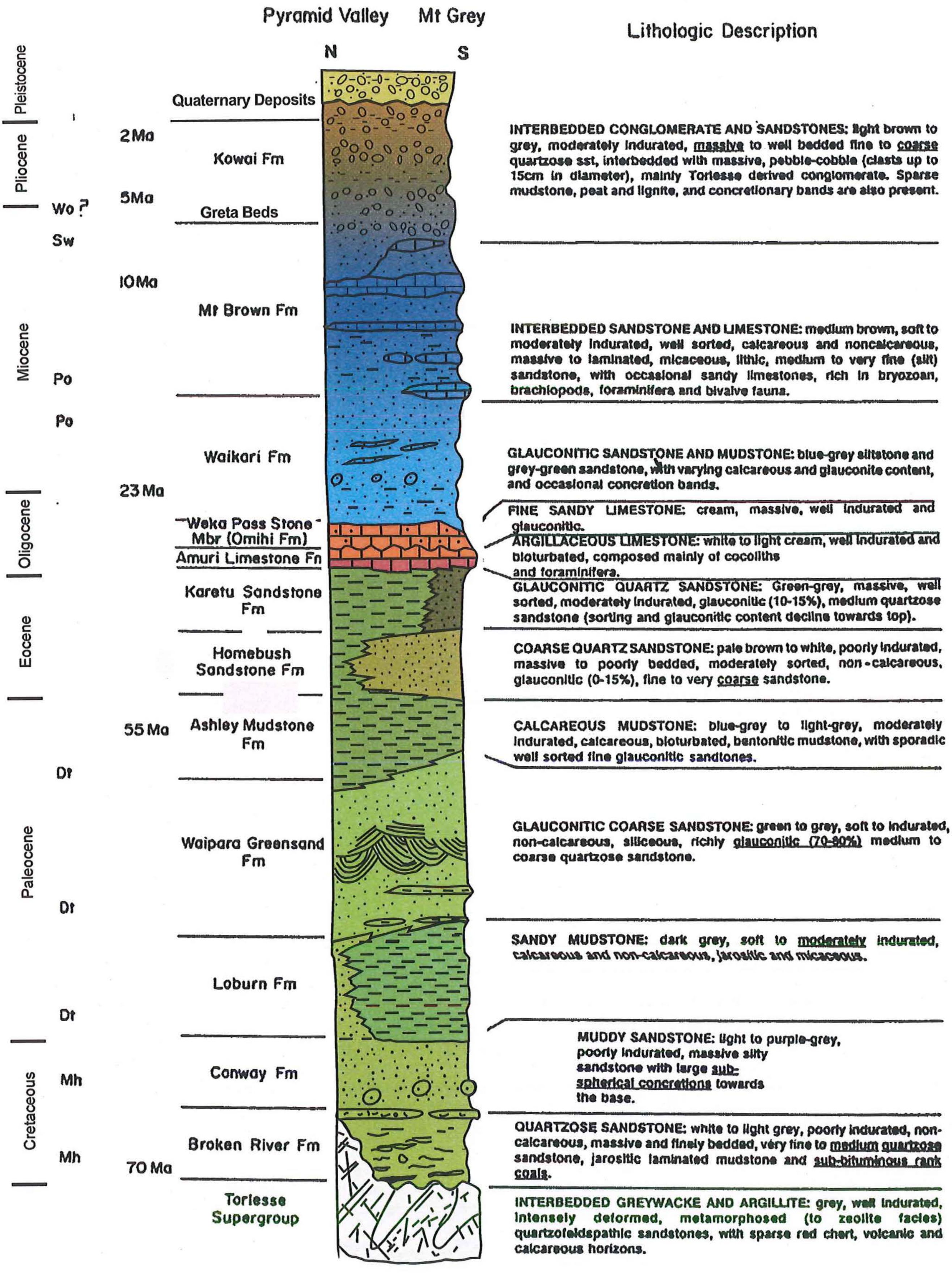

Figure 4.4: Local Stratigraphic Column for the Waipara Region (Modified from Nicol (1991) and Loris (2000). Stratigraphic colours altered to reflect north Canterbury GIS standards).

4.4. Omihi Valley surface and subsurface hydrology:

An understanding of the present and past hydrology of the Omihi Valley is important in characterising the present complex aquifer system. The aquifer units are believed to be fluvial in origin and have been proposed, on the basis of sparse borehole data, to be analogous to the present day fluvial depositional systems (Loris, 2000).

4.4.1. Surface Hydrology:

The surface hydrology of the Omihi Valley has been investigated by several researchers. Lloyd (2002) has quantified the key parameters of the hydrology, including the precipitation and evapo-transpiration rates that dominate the valley's water resources. The lower part of the valley receives only 600-700 mm of precipitation annually, as it is in the rain shadow of Mt Grey and the coastal hills. The Valley's eastern margins and coastal hills (located within the valleys catchment) receive considerably more rainfall (1200-1300 mm/per year) in the upper part of the catchment located in the coastal hills. The precipitation is relatively evenly spread throughout the year, but the available water is controlled by the high evapo-transpiration rates which may peak at 120 mm/per month during the height of summer. Due to the high evapo-transpiration rates significant groundwater recharge and runoff occurs primarily during the winter months. This results in a highly variable flow regime for the streams. The Omihi Stream has a summer flow rate of 250 l/s but 800 l/s during the winter months (Lloyd, 2002).

The present hydrologic regime in the Omihi Valley consists of several streams of the classic meandering model of Miall (1978). The streams have a high sinuosity and low braiding parameter with a variable bed-load sediment type, ranging from gravel (mainly Mezozoic greywacke and argillite derived clasts and sand, to nearly 100% fines (silt/clay) along their course. The streams have low mean flow, but during flood events flow rates increase dramatically reaching an estimated 10-50 times greater (per. comm. A. Munro 2001). These flooding events cause over-bank silt and clay deposition across the extensive active floodplain area.

4.4.2. Groundwater Hydrology:

The Omihi Valley's aquifers consist of a complicated series of inter-connected laterally and vertically heterogeneous paleo-fluvial deposits. The aquifers are of limited thickness (<10 m) have low transmissivity 18-92 m^2/day (Loris, 2000) and have large drawdowns when pumped, compared to wells located elsewhere in Canterbury e.g. (Armstrong, 2000). The aquifers are believed to be zones of cleaner gravels within the Late Quaternary age clay/silt-bound valley fill sediments. Within the Omihi Valley there are four producing wells (not including shallow domestic wells). These wells have an average yield of 16 l/s (Loris, 2000). This yield is higher than the adjacent Waipara Valley where average yields are less than 5 l/s. Recent work by Lloyd (2002) indicates that the Omihi Valley has a net groundwater flow from the valley into the neighbouring Waipara catchment. It is estimated by Lloyd that 49 % of Waipara River net outflow is derived from the Omihi Stream catchment, with only 11 % of the 49 % derived from the surface component of the Omihi Stream. This net flow appears to occur below the depth (50 m) from which most abstraction occurs, and the resource is not heavily exploited. Limited work has been undertaken in the Omihi Valley to define the subsurface hydrologic conditions such as transmissivity, storativity and hydraulic conductivity. Only one pump test has been undertaken on a well within the valley (well N34-0142)[8] (Loris, 2000). The results from this test indicate a high transmissivity of 74-110 m^2/day and a hydraulic conductivity of 6. A feature of this test was that the well N34-0134, 760 m from N34-0142, was affected by the drawdown test while a well N34/0143 which was 1010 m from N34-0142 was not, yet both were believed to have penetrated the same aquifer unit (Appendix 8 - Map 2). Water chemistry research undertaken by Loris (2000) has shown that the northwestern and southeastern sides of the Omihi Valley appear to have different recharge and storage conditions, based on the differing water chemistry of the wells. The STIFF diagrams derived from water chemistry measurements show markedly different cation and anion fractions (Loris, 2000; Fetter, 2001). Well N34-0139 is classified as sodium bicarbonate water, while wells N34-0142 and N34-0134 show high calcium concentrations and are classified as calcium bicarbonate waters. This difference in water chemistry indicates that the wells have similar recharge pathways and different storage conditions, or have different recharge pathways. From topographic considerations it is assumed that recharge of the southeastern wells is from the eastern valley margin or further up the Omihi Valley; while the northwestern side well N34-0139 recharge is derived from the western margin through infiltration of groundwater through the Kowai or Mt Brown Formation. Recharge of well N34-139 directly from water diffusing out of the Omihi Stream, could not be eliminated as the chemistry of the Omihi Stream is not known but little loss of water to groundwater recharge has been

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[8] Well numbering uses the Enviroment Canterbury numbering system. See Appendix 7 for details.

measured in that area of the valley and it is believed that recharge is unlikely to be dominated by the present Omihi Stream.

Several characteristics of the aquifers penetrated by wells indicate that they have a complex geometry, including:

- The producing wells have spatially variable flow (5.9-22.8 l/s).
- The wells have had strong draw-down effects on wells up to 760 m away, yet have negligible effect on wells 300 m further away.
- The aquifer-rich zone from 90-110 m depth is penetrated in several locations close to producing wells (400 m horizontally) and no economic producing horizon was found.
- The producing horizons within the gravel units are thin, less than 10 m and because draw-down is not great, must have a reasonable storage capacity.

This leads to the conclusion that the units are either small, interconnected, discrete aquifers or the aquifers are laterally continuous primarily in one dimension. The preferred model for the near-surface valley fill (< 200 m) is of gravel units that are laterally continuous along the valley axis which are less than 10 m in thickness, and are several hundred metres in length, and in turn connected with other aquifers to form a laterally heterogeneous, interconnected series of lensoidal or flatten pipe like aquifer units (Moreton et al., 2002).

4.4.3. Fluvial History of the Omihi Valley:

The present valley architecture is likely to be representative of the paleo-valley during the Late Quaternary and so a similar drainage system can be inferred. No geomorphic evidence has been found that any major rivers drained the catchment or were diverted through the valley during the Late Quaternary. The flow of the individual paleo-streams within the Omihi catchment is likely to have been variable over the time period that the valley's Late Quaternary sediments were deposited, as climatic conditions would have been variable due to the glacial cycles. During flood events the Omihi Stream continues to use the meandering stream bed and it is expected that the paleo-valley streams demonstrated a similar meandering stream profile during the Late Quaternary. The valley drainage would have been affected by internal and external valley controls, which would have directly controlled aquifer geometry (Miall, 1978).

Assuming that the present catchment has remained of similar size and gradient during the Late Quaternary and that the flow rates have also remained (within an order of magnitude) similar to the present flow rates, it is expect that the Quaternary fill consists of generally meandering stream deposits with a large amount of over-bank fines and near the valley margin alluvial fan derived material.

4.5. Summary:

From pre-existing geologic information, the Omihi Valley appears to be a simple thrust fault controlled valley with the Omihi fault located along the southeast margin of the valley. The post-Kowai Formation Late Quaternary sediments are of unknown thickness, but must be at least 130 m thick in the centre of the valley. Due to the increasing geologic age of outcrop to the north it is believed that the northern portion of the valley had undergone greater differential uplift than the southern portion. This has resulted in a thinning of the Late Quaternary valley fill to the north end of the valley. The aquifer units within the Late Quaternary valley fill sediments are believed to be a laterally heterogeneous interconnected series of lensoidal or flatten pipe-like clean Torlesse derived gravel units deposited by meandering paleo-streams.

Chapter 5. Structural delineation:- subsurface investigations

The purpose of this chapter is to describe the subsurface investigations undertaken to characterize the large-scale geologic structure and lithology of the Omihi Valley. It describes the integrated seismic reflection surveys, field mapping and borehole/well logging which was undertaken.

5.1. Field procedures:

The effectiveness of many "standard" geophysical methods such as ground penetrating radar, TEM, and gravity has been shown to be limited in the unconsolidated Late Quaternary sediments of north Canterbury (Armstrong, 2000; Loris, 2000) (see section 3.2). In order to overcome these limitations seismic reflection surveying was used in this study as it provides good penetration, relatively fast acquisition rates, and interpretation procedures are well developed and understood (see Appendix 6 for details). After field testing of two seismic sources mini-SOSIE and hammer and plate, a hammer and plate seismic source was chosen. For the Omihi Valley structural delineation surveys, this source gives a high frequency signal to depths greater 300 m, which it was anticipated would be sufficient to image the whole of the Late Quaternary succession.

5.1.1. Seismic reflection surveying parameters:

The successful application of active source, shallow seismic surveying, requires acquisition parameters that are tailored to the subsurface conditions present at each survey location. The selection of the optimum parameters can increase the depth to which the subsurface can be imaged, increase lateral and vertical resolution and improve the coherency of the reflector packages. The incorrect application of acquisition parameters can result in very poor records or no interpretable reflection data. The selection of these parameters is accomplished by the use of pre-survey modeling based on the pre-existing geologic information, or by field testing using varying sources and acquisition geometries. If previous seismic reflection surveys have been undertaken in the general vicinity then the parameters used in those surveys may be applied.

Even when the optimum acquisition parameters have been selected the seismic reflection method may not be applicable to a particular part of a study area. The seismic reflection method is strongly dependent on the near surface conditions. Consolidation, moisture content, sorting, grain size and organic content all effect how the acoustic wave is propagated. These subsurface conditions can result in a wave field swamped by ground-roll, trapped waves or refraction reverberations. Therefore the initial stage of the Omihi project involved walk-away field testing of the seismic reflection acquisition parameters to decide if seismic reflection surveying is possible. This was undertaken in October 1999, and demonstrated that the seismic reflection surveying can be successfully applied within the Omihi Valley's near surface (30 - 300 m) sediments. Figure 5.1 shows a representative super-shot gather.

The acquisition of seismic reflection data is a balance between the lateral/vertical quality of the data and the speed of acquisition. The use of small source and receiver intervals and a high frequency seismic source, decreases the minimum size of subsurface features that can be detected and delineated, and increases the signal to noise ratio of the image allowing better interpretation of the seismic section. The use of small shot or receiver intervals also increases acquisition time, reducing the amount of data that can be collected during a field survey or for a set cost. The aim of any seismic survey must be to produce an accurate subsurface image within the time and financial constraints of the survey (Appendix 6).

5.1.1.1. Source Parameters:

The mini-Sosie and hammer and plate source were tested in the Omihi Valley and proved to have similar source wavelet characteristics. Both were shown to produce high frequency reflection energy down to >300 ms, two way time. The hammer and plate source was chosen for further surveying within the valley as acquisition rates are usually an order of magnitude faster for shallow surveying and the source is reliable and cost effective. The hammer and plate source parameters are shown in Appendix 1 for each of the surveys.

5.1.1.2. Receiver and cable parameters:

The seismic acquisition parameters used in the valley were designed to allow rapid and economic determination of the overall valley structure. A forty-eight channel seismograph with 96 channel takeout CMP cables and a 96 - 48 channel roll-along switch was used. Most surveys used an off-end-push, geometry with zero to 25 m offset between the first geophone group and shot (Appendix 6). Geophone strings of three 30 Hz phones were used and the receiver group spacing varied between 2 m and 6 m. Shot spacing was usually twice the group interval and consisted of 6 - 16 stacked hammer impacts per shot location. Receiver and shot locations were surveyed using differential GPS surveying.

5.1.2. Seismic reflection processing flows and velocity analysis

The general seismic reflection processing flow used for each of the structural delineation seismic lines is described in Appendix 6. The processing flows used for the lines was similar with only minor changes to account for the differing acquisition geometries used and near surface effects.

Velocity analysis for the seismic lines was undertaken using standard seismic reflection processing methodologies including: semblance analysis, constant velocity stacks and normal moveout interactive velocity analysis (Yilmaz 1987). Velocity analysis indicated that for most of the seismic reflection lines a NMO velocity model, based on a linear increase in NMO velocity with increasing two way time gave the most coherent and interpretable reflections. It was therefore decided that detailed, time intensive, velocity modelling was not necessary for the near surface reflection data (30 – 300 m) and was not undertaken. Several seismic reflection lines were found to have only minor NMO velocity variation over the depth range of interest (50 – 200 m) and a constant NMO stacking velocity was applied to these seismic sections. The lack of heterogeneity in the near surface velocity model is believed to be related to the general trend of unconsolidated, saturated, near surface sediments being dominated by compaction effects and not sediment matrix and clast mineralogical composition.

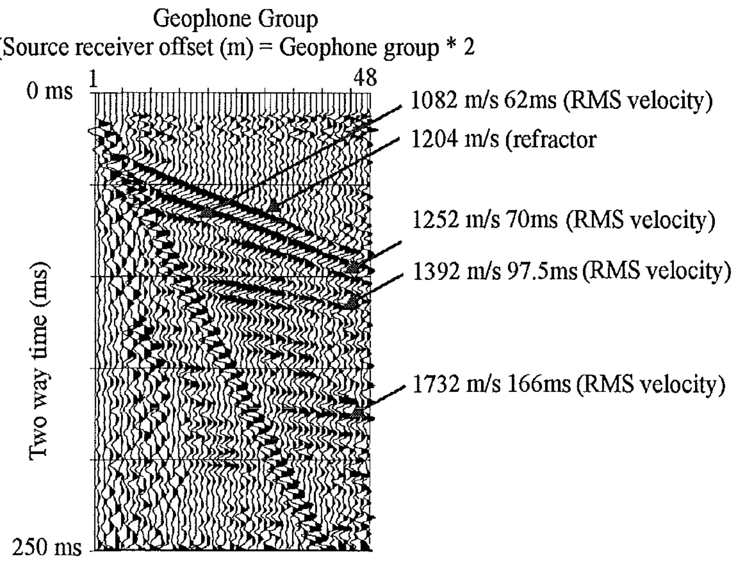


Figure 5.1: Representative super-shot gather showing RMS velocities.

receiver group spacing varied between 2 m and 6 m. Shot spacing was usually twice the group interval and consisted of 6 - 16 stacked hammer impacts per shot location. Receiver and shot locations were surveyed using differential GPS surveying.

5.2. Seismic lines undertaken:

Nine seismic lines, some of which were shot in two or more sections due to restrictions caused by State Highway 1, the main trunk railway line, and the Omihi Stream, were undertaken in the Omihi Valley. The location and extent of these nine lines was controlled by existing borehole locations, planned borehole locations, access, topography, and the need to delineate the structural architecture of the valley and infill while minimising field effort and costs. The seismic lines are described below in chronological order (Appendix 8 - Map 2).

Omihi Line 1

The initial seismic line Omihi-1 was located across the neck of the valley, at the narrowest width. This profile was designed to quantify the major valley structure and lithology and to delineate the location of the Omihi fault and/or associated structural features. The line runs from the change in slope at the northwest valley margin to State Highway 1 on the southeastern valley margin (Figures 5.2 and 5.3).

Omihi Line 1S

Omihi-1 was successful at imaging lithologic and structural detail in the valley and characterised the southern Omihi Valley Late Quaternary stratal architecture. It was therefore decided that a further seismic line adjacent to the southeastern valley margin may be able to characterize the shallow rangefront structure of the Omihi fault, which from geomorphic evidence is inferred to occur in that general area. The seismic line 1S runs from State Highway 1 up the eastern valley margin for 244 m (Figures 5.2 and 5.3).

Omihi Line 2

The second line was a duplicate of a small section of Omihi-1 with smaller geophone and shot spacing. This line was designed to investigate what the lateral and vertical limits of the seismic method are within the Quaternary valley fill. The survey also delineated the near surface (top 200 m) sedimentary packages. It is located along the same line as Omihi-1.

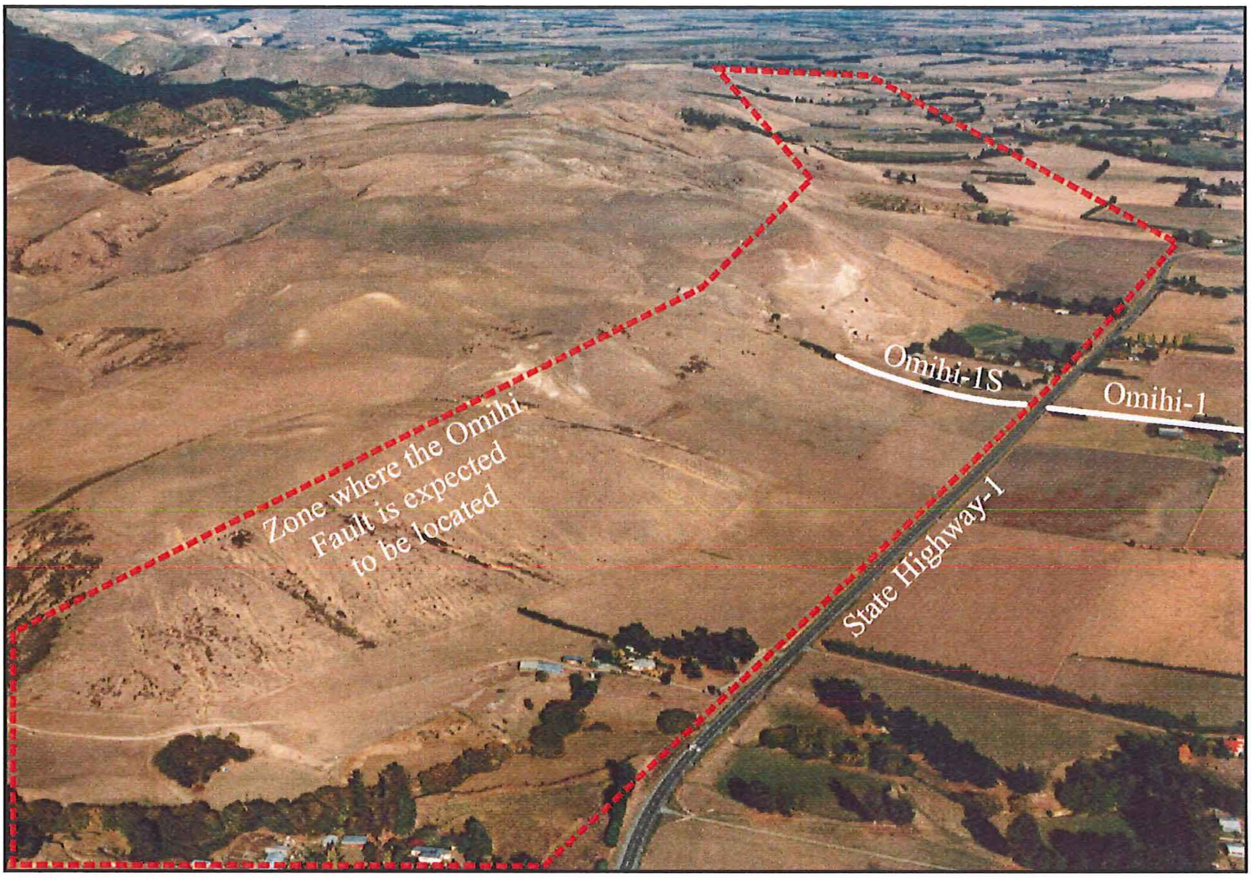


Figure 5.2: Aerial Photograph of the Omihi Fault zone looking Southeast. The location of the two seismic lines Omihi-1S and Omihi-1 (only partially shown), are indicated. Aerial photograph supplied by Mark Armstrong.

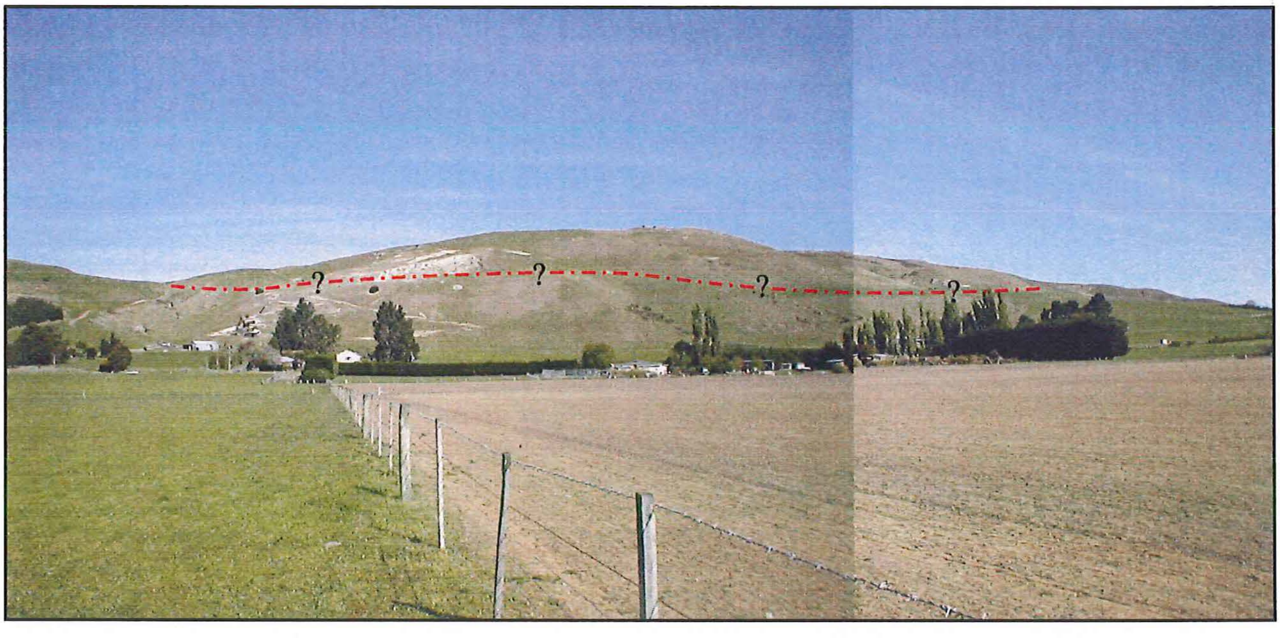


Figure 5.3: Inferred location of the Omihi Fault seen from the southern Omihi Valley floor, looking east.

Omihi Line 3

The deformation history within the valley as seen in outcrop geology is complex and varies along the valley's axis. Seismic Line Omihi-3 was undertaken to delineate these variations in the centre of the valley. The line was also located adjacent to several poorly logged wells and close to where further wells were later drilled. The line ran from the Omihi Stream on the western valley margin to State Highway 1 on the eastern margin.

Omihi Line 3S

This line is an extension to Omihi-3 located on the eastern side of State Highway 1. It runs from the southern side of State Highway 1 until the change in slope on the eastern valley margin.

Omihi Line 3N

This line is an extension to Omihi-3 located on the western side of Omihi Stream. It runs from the Omihi Stream Bank to the change in slope on the valley's western margin.

Omihi Line 3HR

This line is a duplicate of a small section of Omihi-3, along a possible borehole location. The survey parameters were tailored for high resolution, near surface seismic imaging.

Omihi Line 4

This line was designed to delineate the valley structural architecture in a similar manner to the Omihi-1 and Omihi-3 lines, but farther north in the valley. It was also designed to quantify the thickness of the Quaternary fill, which thins to the north. It runs along the length of Jury's Road and across the paddock at the end of the road until the change in slope at the western valley margin.

Omihi Line 5

This line was also designed to delineate the valleys structural architecture in the far north of the valley and image the thickness of the Quaternary fill, if present. It runs from a stream gully several hundred metres to the northwest of State Highway 1, across sheep and crop paddocks, until stopping at a steep gully near the western edge of the valley.

Omihi Line 5S

This line is a portion of Omihi-5 and runs from State Highway 1 to a stream gully where Omihi-5 begins.

Omihi Line 6

This line was added to improve the correlation between the surveys in the south and those in the north. It reduced the need for an extension of the Omihi-7 tie line along the valley axis, which, due to cultural features would have been difficult to complete in the time available. The line runs along a farm track which starts 500 m northwest of State Highway 1 and continues to the Omihi Stream.

Omihi Line 7

This is a tie line between Omihi-1 and Omihi-3, which was initially intended to continue to the north of the valley, however, this continuation was not undertaken, as correlating the general lithology between lines was not found to be difficult and the extra time and expense were unwarranted. The line runs from just southwest of the Omihi-1 (Shot Point 276) to 500 m past Omihi-3 (Shot Point 270).

Omihi Line 8

This high resolution seismic line was located at a possible well location, which was ultimately not drilled.

Omihi Line 9

This was a tie line between well location N34-144 (non-producing) and N34-130 (producing). It was undertaken to assess if lithologic and fluvial architectural changes could be delineated between the two borehole locations.

5.2.1. Topographic data derived from seismic survey lines:

Each seismic reflection line (as well as all roads in the valley) were surveyed using GPS differential techniques. This resulted in seven topographic transects: five across the valley axis and one down valley. These transects were accurate to within the range +/- 20 cm (phase-code processing) and to +/- 1 m (P-code processing) in height depending on the data collection method (Trimble, 2001). The topographic valley profiles are shown above the seismic lines at approximately the correct scale, based on 2000 m/s interval velocity for the seismic lines. A simplified topographic summary of the valley is shown in Tables 5.1 and 5.2.

Topographic Survey location	Slope (Direction)	
Omihi-1 (Seismic Line)	0.8° (Northwest)	Southern part of the valley
Omihi-3 (Seismic Line)	0.56°(Northwest)	↓
Omihi-6 (Seismic Line)	0.086° (Northwest)	↓
Omihi-4 (Seismic Line)	0.16° (Northwest)	↓
Omihi-5 (Seismic Line)	0.25°(Northwest)	Northern part of the valley

Table 5.1 Across valley topographic transects.

Topographic Survey location	Slope (Direction)	
Omihi-7 (Seismic Line)	0.23° (Southwest)	Middle of the southern end of the valley
State Highway-1 (Road)	0.48° (Southwest)	Southeast valley margin

Table 5.2 Down valley, axis, topographic surveys.

Starting at the far south of the valley and progressing northward the topography of the valley floor shows a marked northeast slope which gradually reduces to the north reaching only ≈ 0.2° in the far north of the valley. The longitudinal valley axis shows a general slope of ≈ 0.5° to the southwest, with the alluvial fan surfaces clearly seen on the State Highway-1 line.

5.3.Borehole logs:

Within the field area, five previous deep water wells had been drilled with diameters of 203-305 mm (8-12") and depths of 50-130 m. These wells were logged during drilling as required by local ordinance, but the logging was of variable quality. The logs only allow very limited lithologic information to be obtained, but the depth to water-producing aquifers units is usually carefully recorded. To correlate the new seismic reflection profiles it was necessary to log two wells, drilled on the seismic lines as part of this survey: N34-144 and N34-150. These wells would be logged as accurately as possible considering the drilling method used (rotary drill with foam) and samples taken for later grain size and lithology determination. No geophysical logging was undertaken on the boreholes, as the wells are steel cased and no nuclear borehole logging tools were available. The borehole logs for the two wells are shown in Figure 5.4 and 5.5. Full grain size analysis of all samples was not feasible, so a simple gravel/sand and silt/clay division was undertaken. This allowed the coarse lithologic changes to be determined. It also allowed what is believed to be the main control on aquifer properties in the Omihi Valley Late Quaternary sediments, the fines content (silt/clay) to be quantified. The individual values for each sample have a large error due to the limited sample size (0.6 kg), but care was taken to obtain a representative sample at each sample depth. Each sample was also washed to remove the clay component and digitally photographed to allow weathering and other physical changes to be identified (Appendix 7).

5.4. Lithological borehole logging results:

5.4.1. Borehole N34-144:

The results from the grainsize component analysis, borehole logging and a photographic log of cleaned clast material for well N34-144, indicate five major sedimentary facies, which are described below (Figure 5.4).

***Facies A** (0 - 20 m depth)*

This unit has high (~ 75%) clay content with a minor sand component (≈ 20-30%); no gravel-sized clasts are seen. The unit also includes the thin 0.75m organic top soil profile.

***Facies B** (20 - 50 m depth)*

The percentage of clay and sand/silt is similar to Facies A, but with inter-fingered layers of limestone and Torlesse-derived fine gravel clasts.

***Facies C** (50 - 100 m depth)*

The percentage of clay reduces to a minor component near the base of this unit. The sand component remains constant (≈10%) and the gravel component increases. Torlesse and limestone derived clasts are equally represented.

***Facies D** (100 - 180 m depth)*

The percentage of gravel remains high throughout this unit, and the sand content also increases. The gravel clasts are Torlesse derived, and in the lower part of the unit inter-fingered clay layers are present.

***Facies E** (180 - 200 m depth)*

The percentage of gravel is 90%, with minor sand and clay present (≈10 %). The clasts are all Torlesse-derived material and are estimated from the drill log to be boulder size and smaller.

5.4.2. Borehole N34-150:

The results from borehole N34-150 indicate three or four major sedimentary facies, which are described below (Figure 5.5).

***Facies A** (0 - 11 m depth)*

A similar unit to that seen in borehole N34-0144 but reduced in thickness. It is a high (~ 75%) clay content unit with minor sand component (~20-30%), no gravel clasts are present.

***Facies B** (11 - 16 m depth)*

The percentage of clay and sand/silt is similar to Facies A, but with inter-fingered layers of limestone and Torlesse-derived fine gravel clasts.

***Facies C** (16 - 45 m depth)*

The percentage of clay reduces to a minor component near the base of this unit. The silt/sand component remains constant (≈10%) and the gravel component increases. Torlesse and limestone clasts are equally represented.

***Facies D** (45 - 102 m depth)*

The percentage of gravel remains high throughout this unit, and the sand content also increases. The gravel clasts are Torlesse derived and in the lower part of the unit are inter-fingered clay layers.

5.4.3. Well N34-139:

This production well, which was logged by the driller and landowner can be seen in Figure 5.6. The log is of unknown quality and sedimentological facies interpretation is therefore likely to be poorly constrained.

***Facies A** (0 - 3 m depth)*

A similar unit to that seen in borehole N34-144 and N34-150 but reduced in thickness. It has a high clay content with no gravel clasts. The facies also includes a thin (0.3 m) organic top soil layer.

***Facies B+C** (3 - 28 m depth)*

Based on limestone clasts being present throughout this unit, it is assumed that the unit contains both Facies B and Facies C, but as no grain-size analyses were undertaken the two facies can not be differentiated.

***Facies D** (28 - 123 m depth)*

This facies has a high Torlesse clast fraction and minor sand component. From the drilling log it appears to be similar to Facies D seen boreholes, N34-144 and N34-150.

Facies E (123 – 137 m)*

This facies appears to be related to the Facies E also seen in N34-144. It has a marine or estarine component.

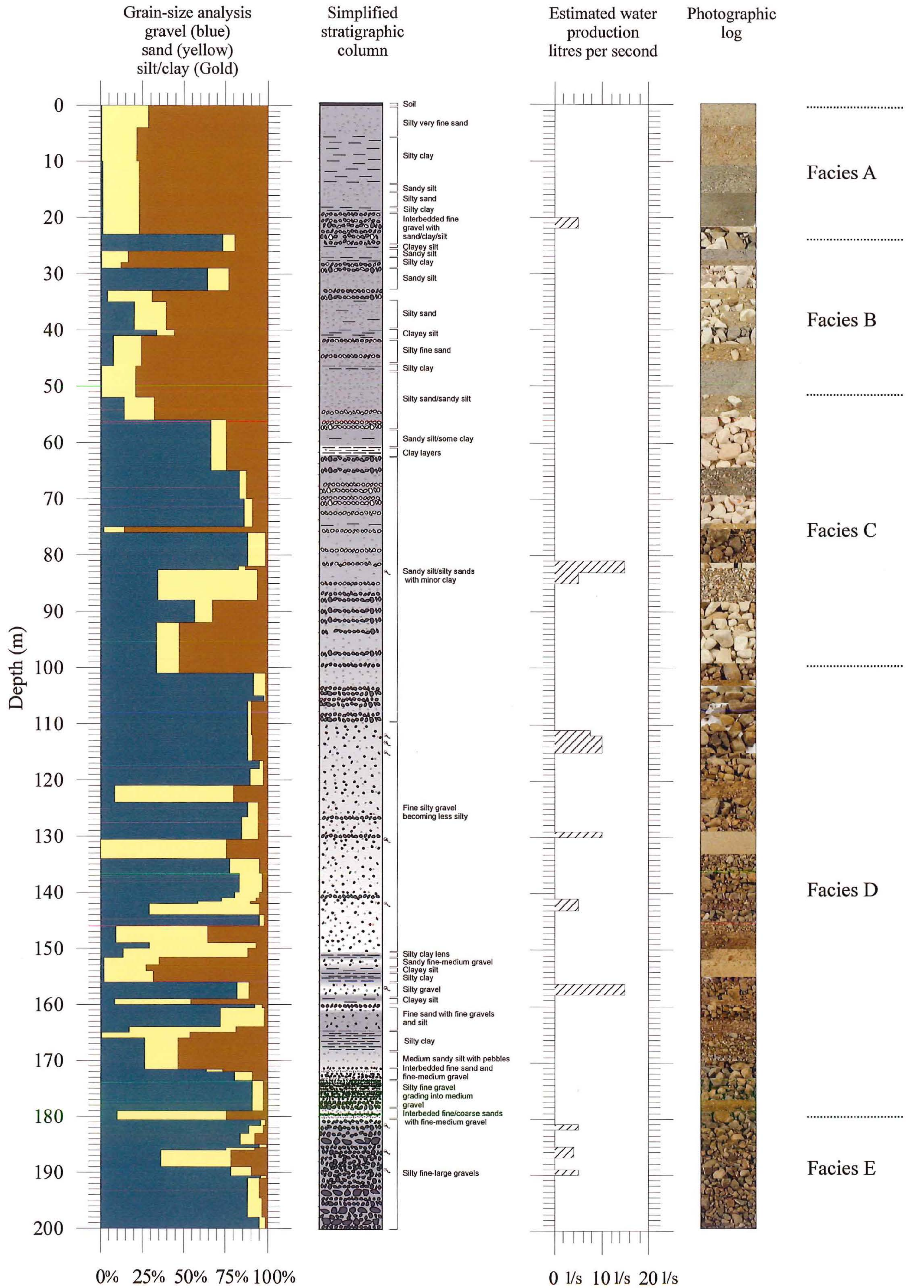


Figure 5.4: Stratigraphic log for borehole N34-144 and interpreted sedimentological facies.

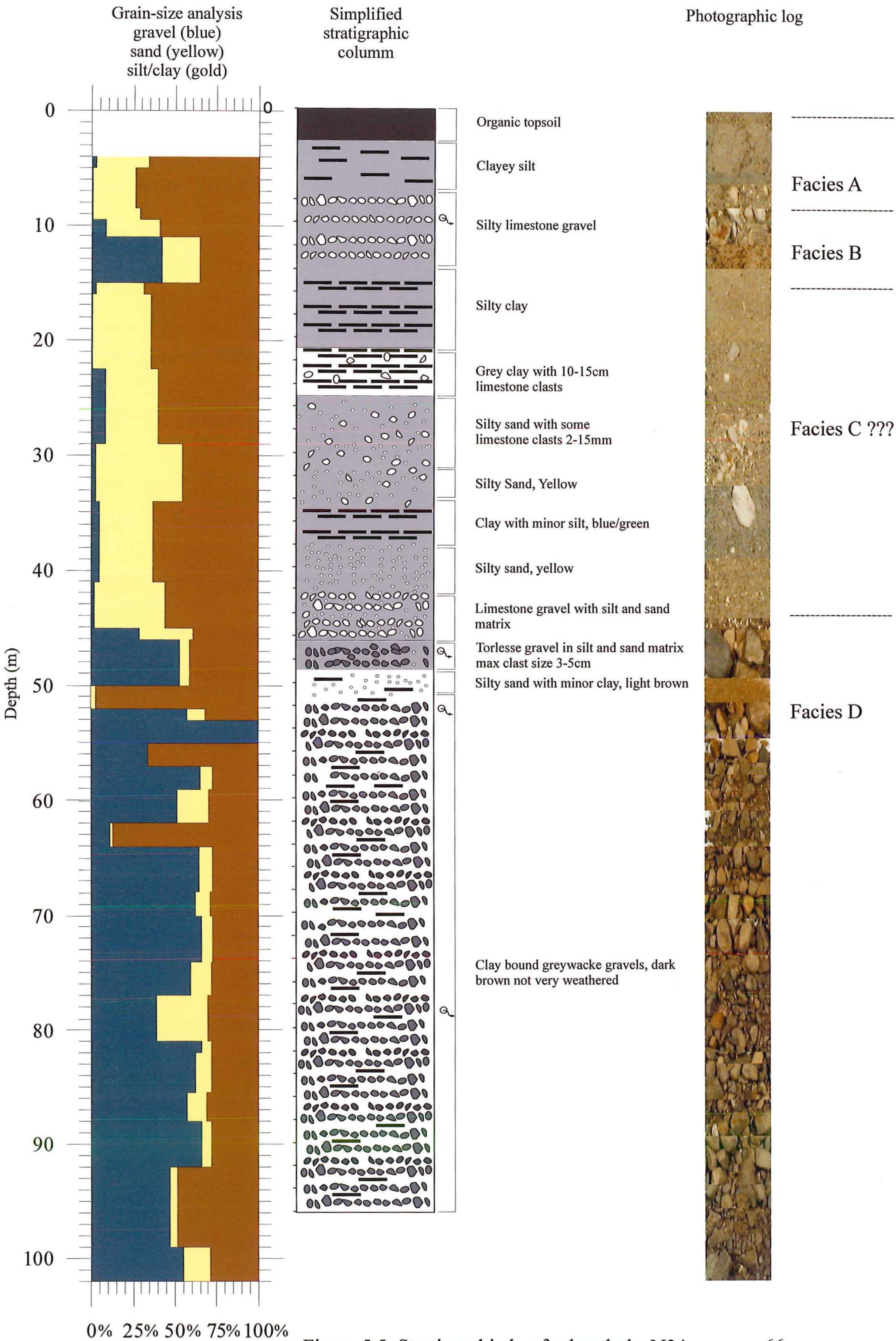


Figure 5.5: Stratigraphic log for borehole N34-150 and interpreted sedimentological facies.

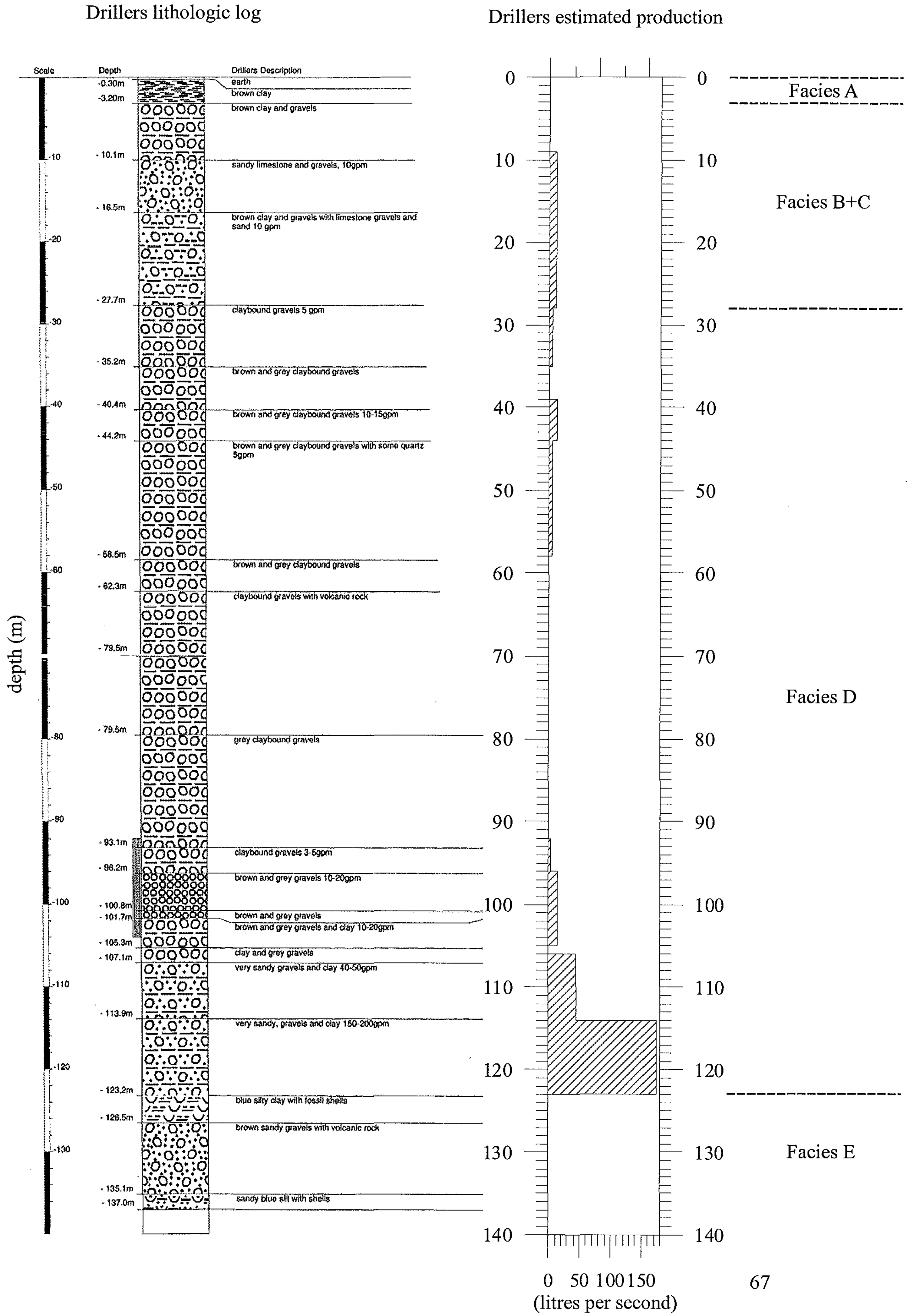


Figure 5.6: N34-139 Well Log.

5.4.4. Facies model interpretation:

Facies A: This facies is inferred to be fluvially transported fines reworked from the valley margin alluvial fans and hillslope loess deposits. The absence of larger gravel clast material indicates a low energy environment and may represent over-bank fines deposition across the floodplain, during flood events. The thickness of the organic top soil profile indicates that the valley has had sufficient time to generate a thick soil profile over most of the valley floor.

Facies B: This facies is inferred to be material transported from the valley margins during a period of high fluvial flow and uplift of the surrounding valley margins. The unit appears to be reduced in thickness in borehole N34-150 but this is expected, as the borehole is coincident with the western margin of the Late Quaternary syncline structure.

Facies C: This facies is inferred to represent a change in the sediment type that is being eroded at the valley margins and surrounding catchments. The Omihi fault and associated faults caused differential uplift, which caused new lithologies to be exposed and eroded. The Limestone clasts derived from the Amuri Limestone Formation found extensively outcropping east of the Omihi Valley. Facies C is not seen clearly in borehole N34-150 and may be absent due to the location of the borehole on the synclinal margin or be too far to the northwest for sediments of Facies C to be deposited.

Facies D: This facies is inferred to represent an early stage in the development of the valley when Torlesse derived material was deposited from a provenance source outside the present catchment of the Omihi Valley. The sediments may represent reworked Kowai Gravel material that has eroded from the growing valley margin during the early stages of the Omihi Valley's development in response to structural deformation.

Facies E: This facies is inferred to be the Kowai Gravel (Kowai Formation), which was deposited in this region of north Canterbury during the Early Quaternary (see chapter 4.3.4). The highly-weathered, large clast size indicates that the gravel clasts are likely to be derived from a nearby source and older than the moderately weathered gravels clasts overlying them. This facies is not seen in borehole N34-150, but this is probably due to the borehole being too shallow to intercept the facies.

Facies E*: This facies may represent the lower Kowai Formation below the Kowai Gravel unit or a laterally variable unit within the Kowai Gravel. In either case the facies is the present hydrological basement for the Omihi Valley.

5.5. Lithologic and structural model based on seismic reflection results:

The seismic reflection profiles (Omihi 1 - 9) (Figures 5.8 – 5.13 and Appendix 1-Sheet 1-Sheet 3) show clear interpretable reflections to over 200 ms TWT (≈200 m) and on several lines to over 700 ms (≈ 700 m). Multiple reflection energy is not a major problem, but refraction energy on most lines swamps the very near surface reflections resulting in no positively identifiable reflectors with in the top ~ 50 ms TWT (~ 30 m).

The seismic lines are best interpreted when they are located in their correct (relative) geometric position, in three-dimensions (Figure 5.7). This allows reflection horizons to be correlated from one seismic line to another and large-scale features to be recognized. Incorporating the valley topographic surface within this model also allows dip slopes to be easily interprelated below the surface and matched with seismic reflection horizons. The ability to rotate and view the reflector features in three dimensions allows the lateral extent of faults, folds, erosional/deposition unconformities and lithologic horizons to be quickly identified. The interpretation package used was Seismic-micro Kingdom Suite © and the project files can be found on CD-ROM-1. Figure 5.7 shows an example of the seismic lines and topography for the Omihi Valley.

5.5.1. General seismic facies model:

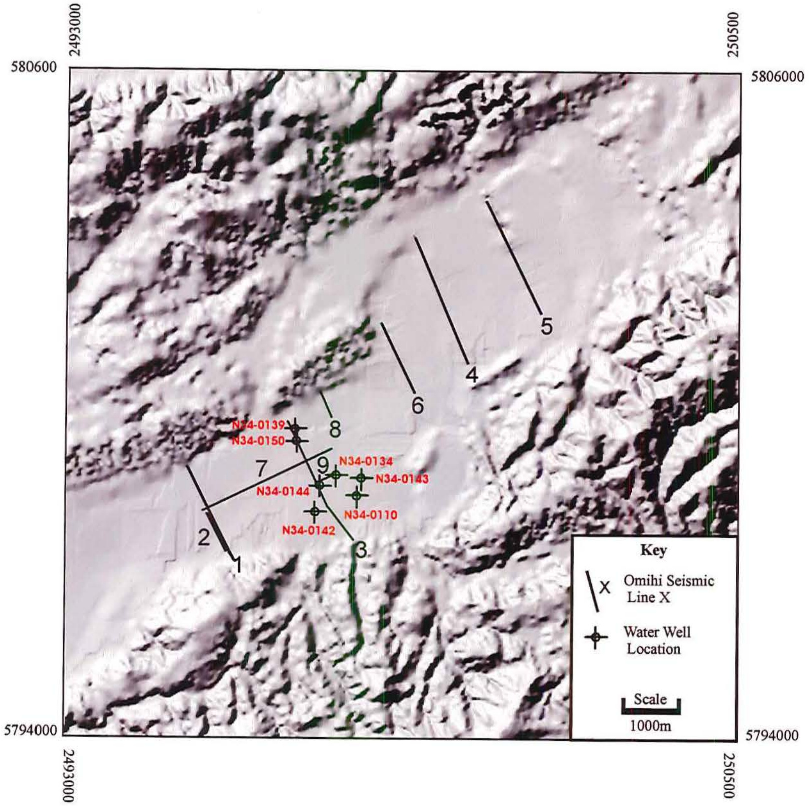
A four-stage seismic facies model is defined, based on the seismic character of several units seen throughout the Omihi Valley. These facies are described below:

Seismic facies 1 – (Thickness ≈ 200 m)

Strong horizontal to sub-horizontal reflectors with a minor wavy component. The large-scale reflector packages are continuous, but individual reflectors are discontinuous. The individual reflectors are closely spaced.

Note: The correlation seen between reflectors in Omihi Line 1 and Omihi Line 3, and the tie line Omihi Line 7, is not exact due to limitations in the three dimensional display software used. Each seismic reflection line is assigned an average topographic height from which the seismic lines are then draped. This results in some discrepancies between reflector packages where topographic changes are significant in comparison to the average topographic height used. This discrepancy has been taken into account during interpretation of the individual seismic lines.

Interpretation undertaken using the Kingdom Suite from Seismic Micro-Technology, Inc.



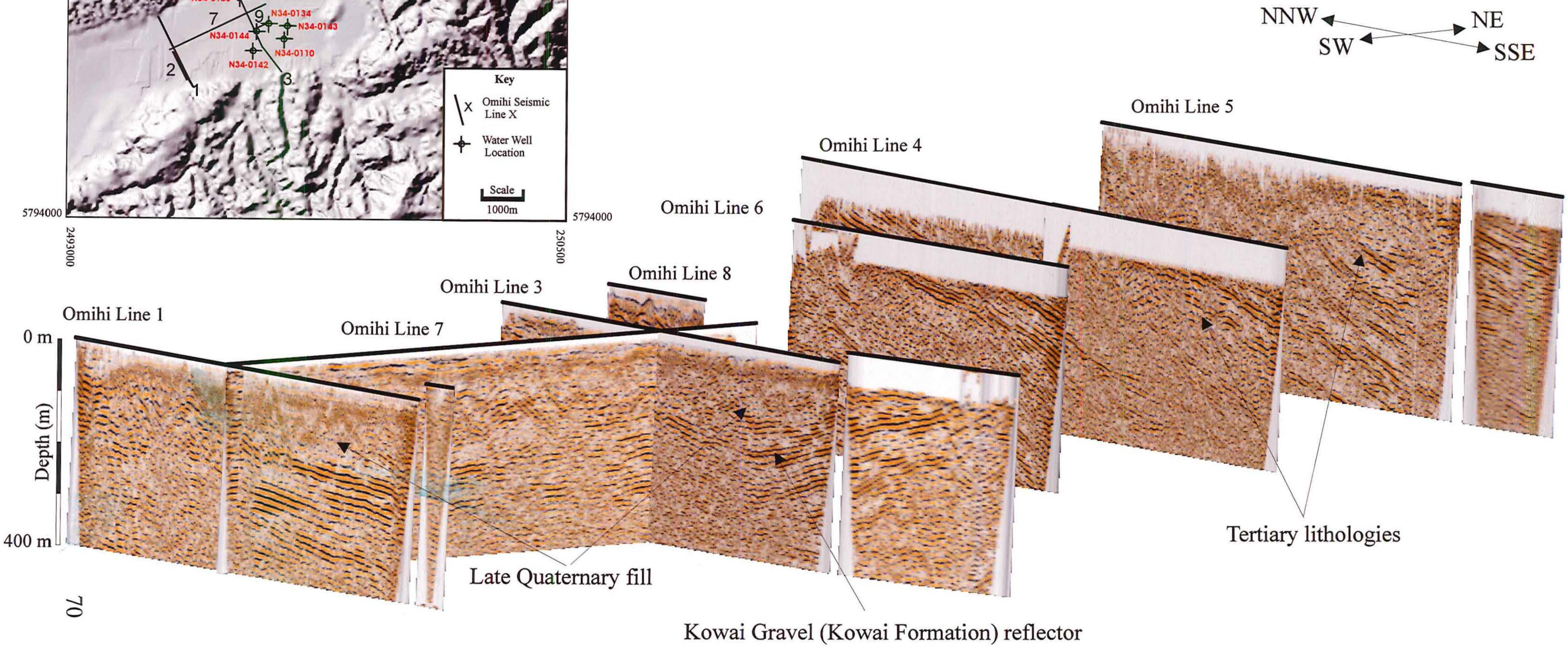


Figure 5.7: All Omihi Valley seismic reflection lines shown in their correct relative three-dimensional position. Insert shows location the field area in the Omihi Valley and shallow seismic reflection lines undertaken. New Zealand Map Grid NZMG 260.

Seismic facies 2 - (Thickness ≈150 m)

This seismic facies consists of a strong reflector, which is laterally continuous, has variable dip depending on location and has reflectors downlapping onto it. It also has a package of weaker, hummocky, discontinuous reflectors below it and is located stratigraphically below seismic facies 1.

Seismic facies 3 – (Thickness ≈ 250 m)

This facies sits directly below seismic facies 2 and consists of sets of dipping strong reflectors, which are continuous over several hundred metres, but do not form a continuous reflector. They are horizontal to sub horizontal with a complex geometry.

Seismic facies 4 – (Thickness ≈ 250 m)

A series of very strong continuous dipping reflectors. Minor warping is evident.

5.5.2. Correlation of seismic facies model with lithology:

Correlating the seismic facies with known borehole, outcrop and previous seismic reflection data (Jongerius and Helbig, 1988) allows the subsurface geology to be defined and correlated.

Seismic facies 1

This facies is correlated with the late Quaternary, post-Kowai Formation valley infill fill. The facies is well constrained by boreholes in the centre of the valley, which have penetrated this unit. No absolute age for the material is available, but from the weathering of the gravels, stratigraphic location and previous work, this unit is known to be Late Quaternary in age. The sediments are a complex series of alluvially and fluvially derived, horizontal to sub-horizontal beds consisting of gravels, sand, silt and clay layers. The unit can be further divided into a younger Canterbury unit (1-80 kyr) and older Teviotdale unit (100-200 kyr) (Yousif, 1988; Nicol et al., 1994; Loris, 2000).

Seismic facies 2

This facies is correlated with the early to mid Quaternary Kowai Formation (0.6-2 myr) and the Kowai Gravel member within that formation and Greta Beds (4-6 myr). The Kowai Gravel unit has a unique signature, corresponding to a rapid increase in clast size (borehole N34-144), weathering of the Torlesse gravel clasts and high fines (silt/clay) content. The top of the formation also outcrops on the northwest margin of the valley and dips below the surface in Omihi Line 3.

The Kowai Formation has a thickness of 563m at the Kowai-1 well (20 km to the southwest) (Brown et al., 1988). The top of the Kowai Formation in the Kowai-1 well is a conglomerate gravel. Conglomerate gravel is generally sparse within the Kowai Formation except in the top 100 m. From borehole logging and seismic reflection data in the Omihi Valley it is known that the Kowai Formation is ~200 m thick. As the Kowai Gravel member of the Kowai Formation is either partially or fully still intact within the Omihi Valley it is assumed that the majority of the Kowai Formation stratigraphic sequence is intact but of reduced thickness compared to the Kowai-1 well. This implies that the Kowai Formation is variable in thickness and may be affected by paleo-topography or a variable depositional environment resulting in variable formation thickness.

Seismic facies 3

This facies represents a complex set of large-scale (> 100 m lateral) units. This facies is not penetrated by any well but can be tracked to outcrop of Mt Brown Formation around the valley margins. The complex contorted character of the seismic reflectors is not seen in the lower seismic reflectors and does not appear to be the result of faulting and deformation. The character appears to be the result of depositional or erosional processes. The Mt Brown Formation in outcrop includes units which have a complex erosional and depositional sedimentary architecture and variable cementation. Facies 3 is therefore believed to represent the Mt Brown Formation.

Seismic facies 4

This facies represents a set of very strong reflectors, and are imaged down to > 600 m (Omihi line 6). These are therefore interpreted to represent a strong lithologic and acoustic impedance contrast. This may represent a limestone unit, which from previous work in Canterbury is known to produce a distinctive seismic signature. This formation is again seen in outcrop on the western valley margin. The correlation between this seismic facies and the Waikari/Omihi Formations is less certain as the formations outcrops further from the valley axis and therefore correlating the units, using surface derived dips, becomes less accurate.

5.5.3. Detailed seismic interpretation for Omihi lines 1-9:

***Omihi-1, 1S and 2** (Figure 5.8)*

These three lines are interpreted as one profile across the valley. They show clearly that the major, near-surface lithology, is dipping and thickening to the southeast. Several major reflector packages are shown in Figure 5.8 and are described below:

A. A strong, very near-surface, horizontal reflector. This package is the result of incorrectly muted refraction energy and should be ignored in any reflection interpretation. The effect of the correct careful muting of this energy can be seen in Figure 5.8 where a small section of line Omihi-1 was repeated using smaller geophone and shot spacing. It can be seen that any events in the top 50 ms should be carefully analysed before assigning a reflection interpretation.

B. This package can be seen to occur from Shot Point 1 - 300 (50 - 200 ms TWT). It contains discontinuous, hummocky, high-reflection amplitude events. Its appearance indicates a reworked or high-energy environment, or a zone of active deformation with multiple fault segments (not all shown). A backthrust fault appears to have offset the Kowai Gravel reflector on the northwestern end of the line and appears to have caused deformation of the underlying Mt Brown Formation.

C. This package has several high amplitude, continuous dipping reflectors and corresponds to seismic facies 1. The major reflectors are interpreted to be changes in late Quaternary lithology, while the smaller scale reflection architecture is assumed to be paleo-fluvial sedimentary packages within the massive sedimentary fill. The major reflectors can be seen to onlap the post-Kowai Gravel reflector and show thinning to the northwest. Many small-scale faults and warping of the reflectors can be seen, but no large fault offsets are depicted. The fault appears to be closer to the southern margin and the minor deformation seen in the package may therefore represent minor thrust faults propagating into the footwall west of the Omihi Fault. The shallow reflectors show less dip than the deeper ones indicating that deformation has been ongoing since the mid Quaternary. The same package of reflectors on Omihi 1S show a contorted and warped character. This is believed to represent the deformation in the footwall adjacent to the main Omihi Fault Zone with the fault located about 100 m to the south east (about 1/3 of the way up the southeastern valley margin). Overall the reflector configuration indicates either dominance of fans from the southeast valley margin or structural deformation.

D. This package is over 300 ms (≈ 300 m) in depth and appears not to be a multiple of earlier events. It has similar dip to the reflectors in package C. The depth indicates that this package may represent a unit within the Mt Brown Formation or possibly the underlying Waikari Formation.

Omihi-3, 3S, 3N, 3HR *(Figure 5.9)*

These four lines clearly show that the Omihi Valley near the Omihi Township, has a synclinal subsurface structure. The deepest part of the syncline is located at SP 110 on Omihi line 3. Several major seismic packages are identified:

A. Unmuted refraction energy.
B. Strong reflectors with a discontinuous, chaotic, hummocky appearance. This package is the same as seismic facies 2 and is correlated with the Kowai Formation reflection packages generally dipping to the southeast. They becoming more continuous and higher amplitude to the southeast.
C. A very strong continuous reflector that can be seen across the whole valley, becoming less continuous near the northwestern end of Omihi 3 and 3S. This reflector is correlated with the top of the Kowai Gravels.
D. This package of reflectors is correlated with seismic facies 1 and represents the late Quaternary valley fill. The Quaternary valley fill seen in the seismic sections clearly shows onlap onto the Kowai Gravel surface. The deeper reflectors are also warped. This warping reduces as the depth decreases. This implies that the synclinal deformation occurred after the deposition of the Kowai Gravel horizon and was ongoing during the deposition of the Late Quaternary valley fill. Only minor warping of the very shallowest reflectors 50 ms TWT (30 m) can be seen.
E. Only on Omihi 3N can a deep reflector be seen 500 - 650 ms (500 - 650 m). This is probably due to the acquisition parameters chosen. This reflector shows that, at depth, the dips are very similar to those found in the younger lithologies of Mid Quaternary age.

Omihi -4A, 4B, 5, 5S, 6 *(Figures 5.10,5.11,5.12)*

These five lines show better penetration than the lines located in the southern part of the Omihi Valley. Seismic section Omihi-6 shows exceptional penetration with strong reflectors visible to over 600 ms TWT (≈ 600 m). The seismic sections clearly show structural and lithologic detail down to > 500 m. The four general seismic facies are seen on all the seismic sections (Omihi-4A, 4B, 5N, 5S and 6) and show similar apparent dips and seismic character. Minor fault trace offsets can be seen in most of the seismic sections within the pre-early Pliocene lithologies, but the complex nature of the lithologies makes detailed interpretation difficult. The seismic sections also indicate that the Late Quaternary sedimentary valley infill is of less thickness than it is further to the southeast. Assuming that change from less coherent, hummocky high amplitude reflectors to much more consistent northwest dipping reflectors is the Quaternary-Tertiary boundary, the Quaternary fill is between 300 m (300 ms TWT) in the southeast of the Omihi Valley and 100 m (100 ms TWT) at the northwest of the Valley.

Omihi-7 *(Figure 5.13)*

This valley axis seismic tie line shows that the near surface Quaternary fill has some (along) axis complexity. Several large-scale (> 250 m) upward convex structures can be seen in the top 100 ms and these are believed to represent alluvial fan deposits that have built out into the valley. Onlap is recognised in several locations along the profile. This may represent the trapping of the paleo-drainage between the fan surfaces. Penetration below the Kowai Formation is poor but there are hints at Mt Brown Formation heterogeneity below 100-120 m (100-120 ms TWT). Fault traces have been identified within the Late Quaternary valley infill but these may represent complex paleo-alluvial and fluvial architecture rather than fault offsets.

Omihi-8 *(Figure 5.14)*

Interpretation of Omihi-8 is constrained by the lack of tie lines nearby and the fact that no boreholes are located within 750 m of the profile. Based on the assumption that the reflector packages seen in Omihi–3 are repeated in Omihi-8, and that the Kowai Gravel which is seen in outcrop at the northwestern end of the line continues to dip at the same apparent angle, it is believed that the line shows Kowai Gravel dipping to the southeast with a complex series of erosional and deposition features. An alternative, preferred interpretation is that the section shows a series of stacked channels that have eroded into the underlying Kowai or Mt Brown Formations and then in-filled during later stream channel migration or alluvial fan out-building. The reflector configurations seen in the seismic section are assumed to be of sedimentary origin and appear to show several paleo-channel-like features.

Omihi-9 *(Figure 5.15)*

This high-resolution seismic line shows seismic facies 1 and 2 only. The line was designed to identify any seismic character change between a producing and non-producing well (see Chapter 6). From the seismic section it can be seen that the seismic character adjacent to N34-144 (non-producing) is dominated by horizontal to sub-horizontal repetitive reflectors from 40 ms - 190 ms. The producing well (N34-134), on the other hand, shows similar reflector character over most of its depth range, but a much more contorted and complex reflector arrangement between 90 –130 ms. The continuous high amplitude repetitive reflectors are believed to represent the majority of the valley infill, which consists of alternative layers of alluvial fan and fluvially derived gravel/sand/silt sheets. The discontinuous complex reflector package may therefore represent a different type of sediment unit, such as a fluvial channel system.

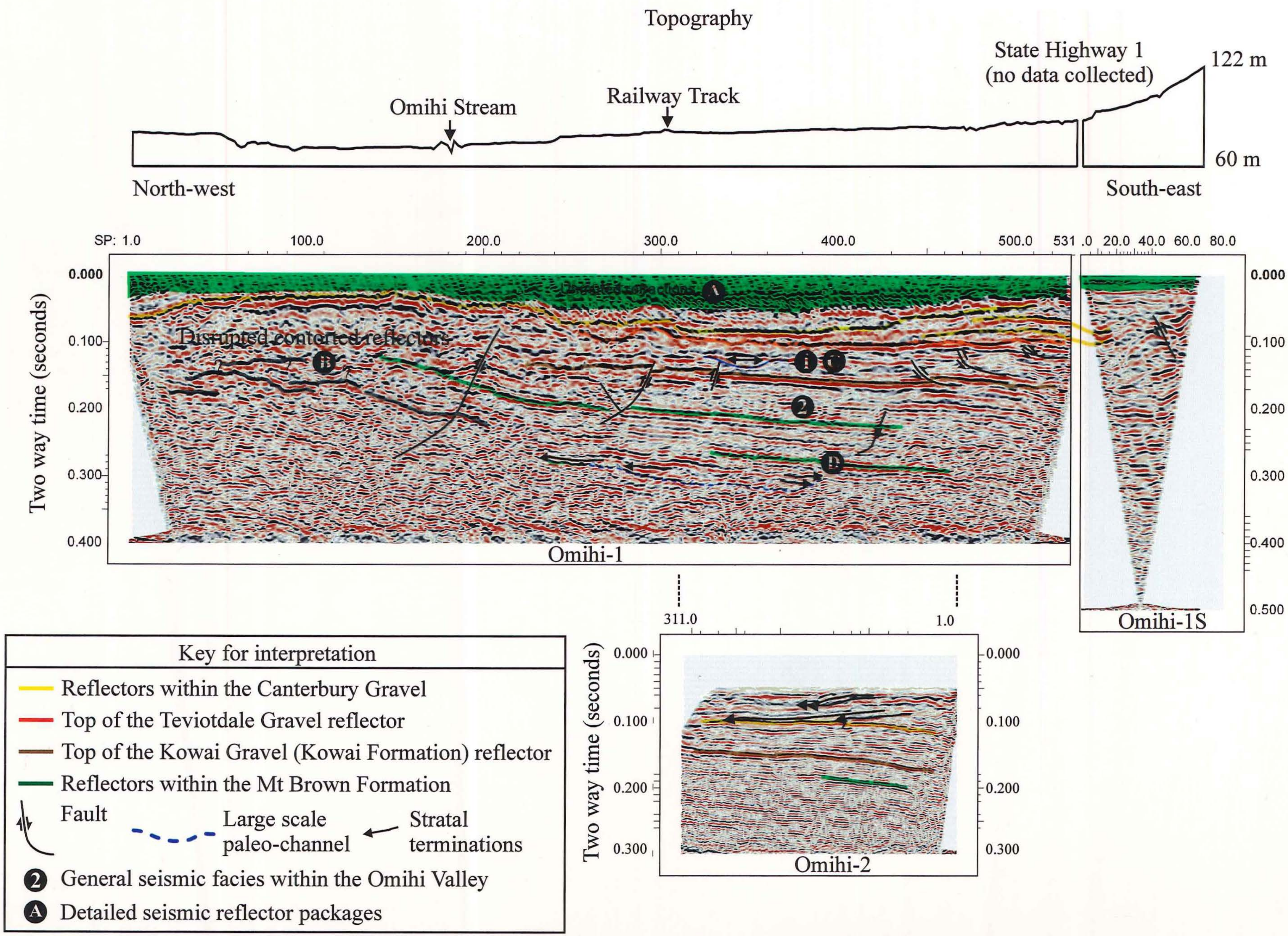


Figure 5.8: Processed seismic sections Omihi-1, 1S, 2 with overlay showing facies and lithologic correlations.. Vertical exaggeration 1.5:1.

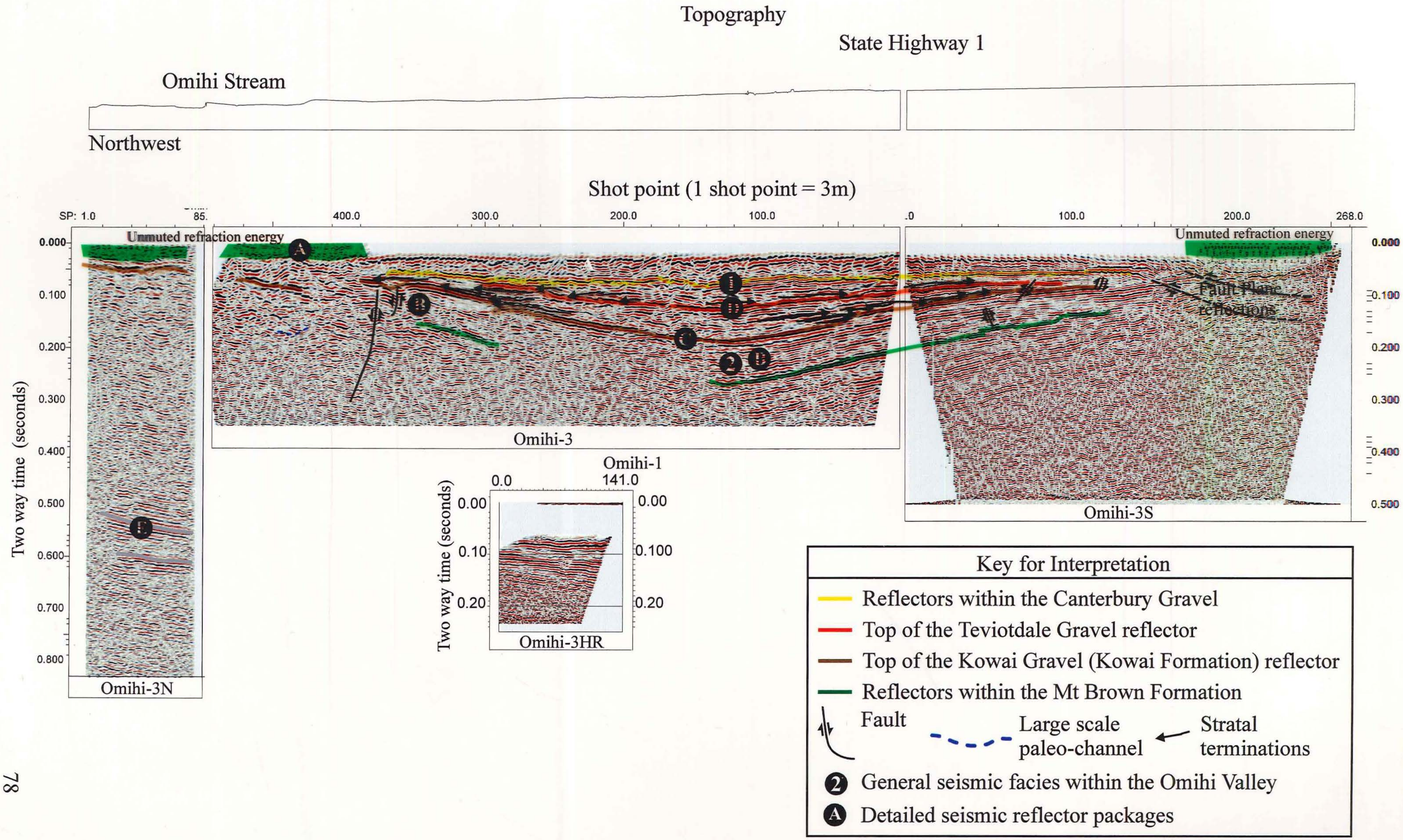


Figure 5.9: Processed seismic lines Omihi-3, 3S, 3N, 3HR. Vertical exaggeration 1.5:1

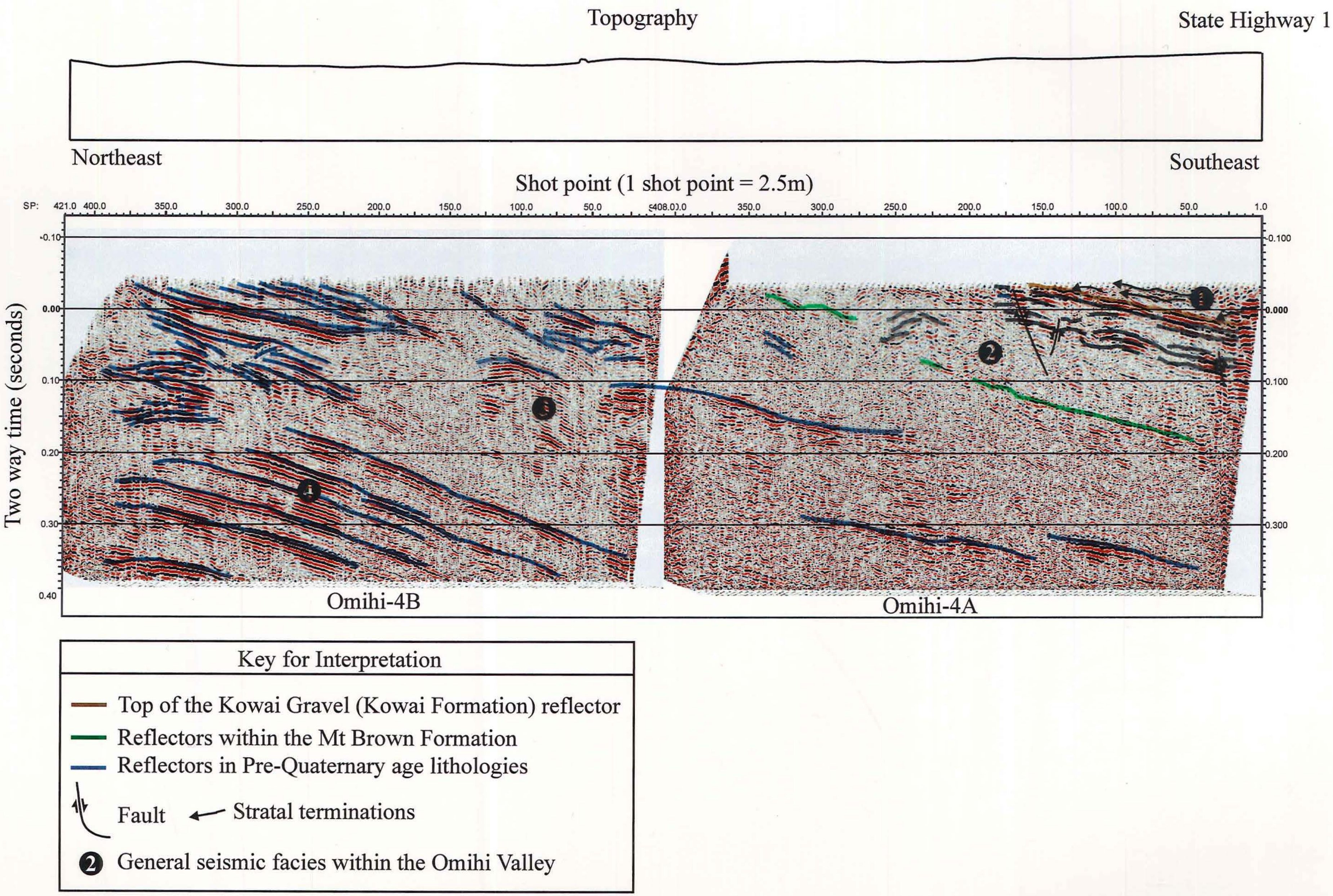


Figure 5.10: Processed seismic sections for Omihi-4A and Omihi-4B. Vertical exaggeration 1.5:1.

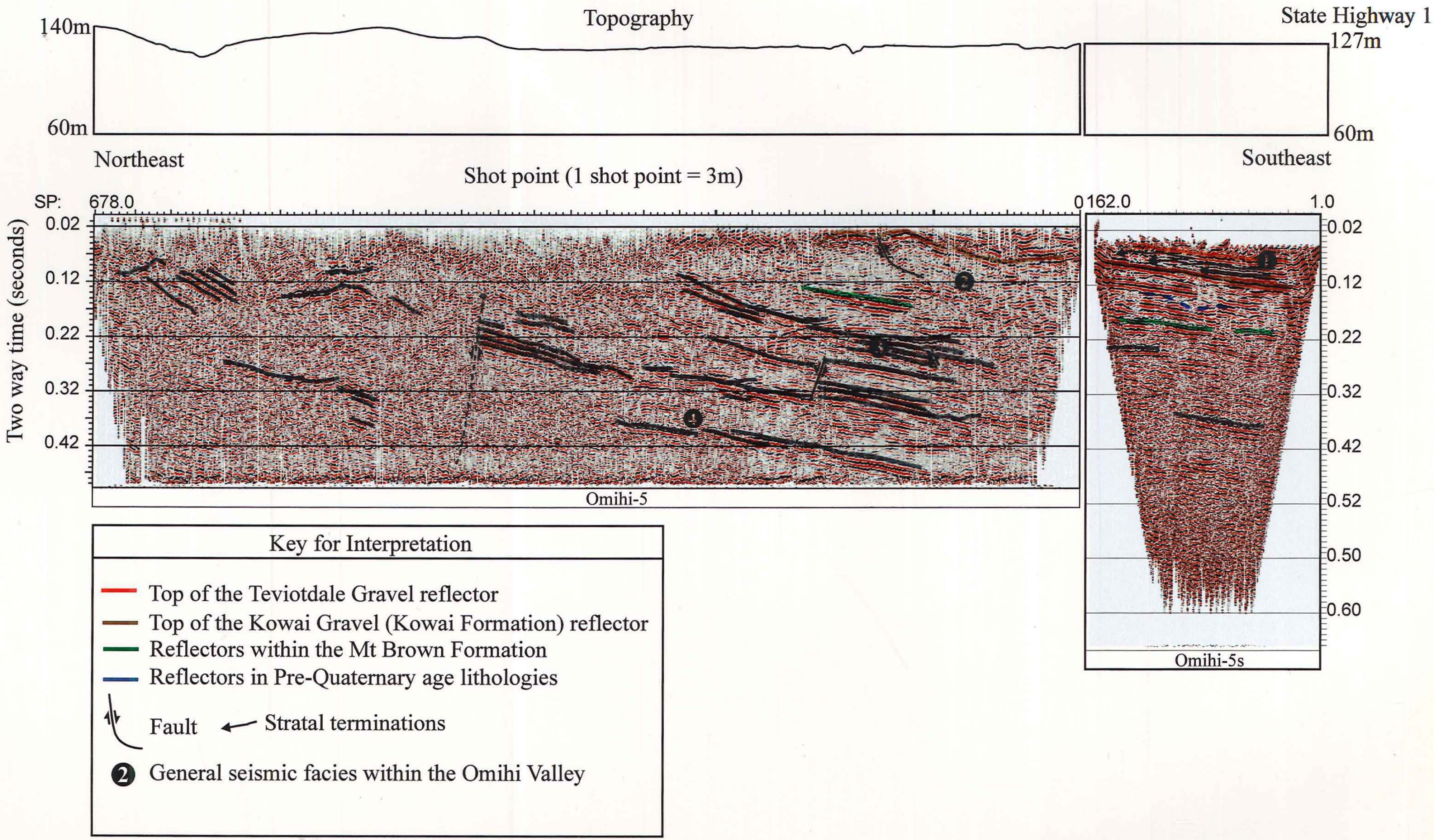
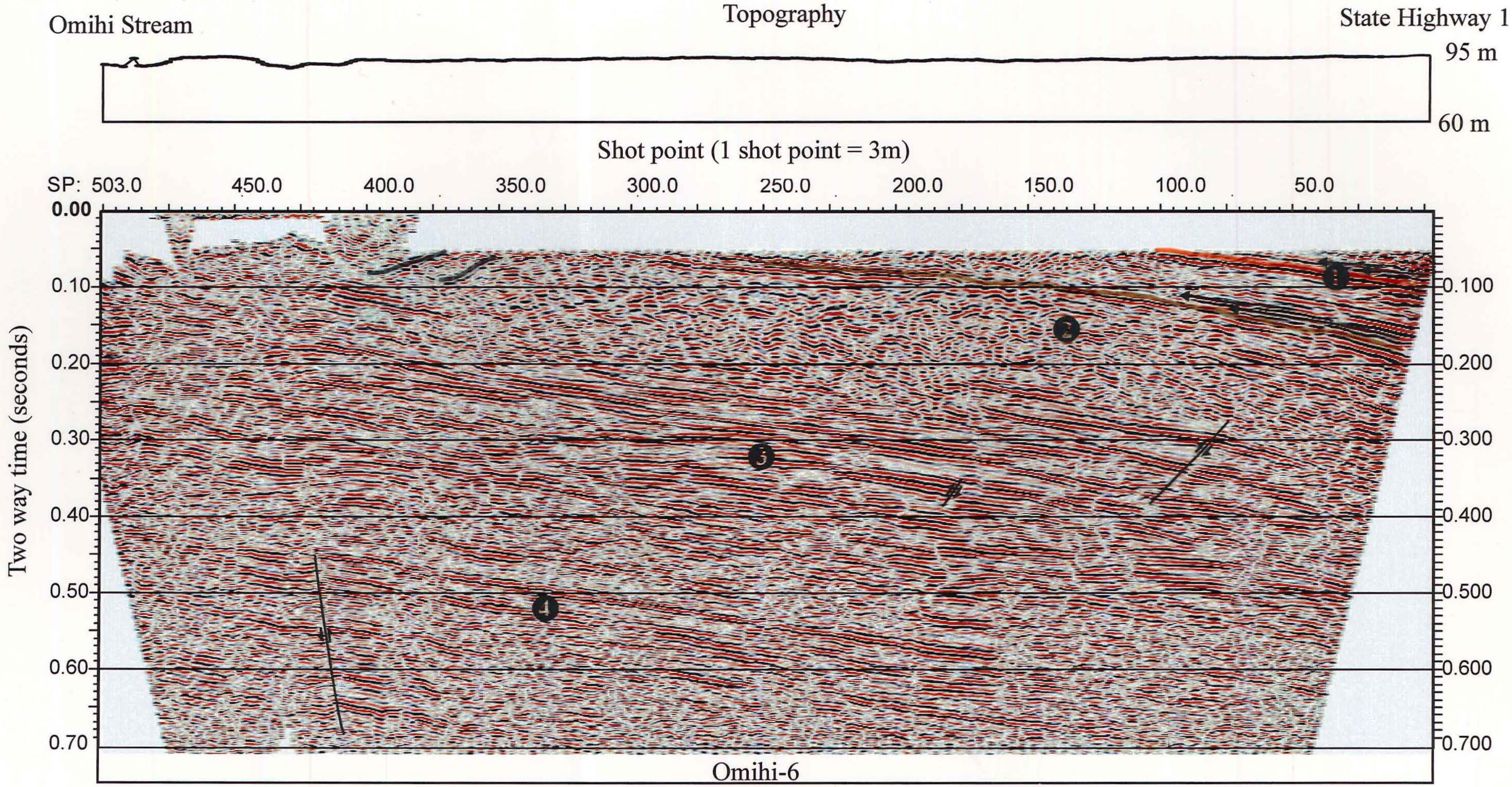


Figure 5.11: Processed seismic sections for Omihi-5 and Omihi-5S. Vertical exaggeration 1.5:1.



Key for Interpretation

- Top of the Teviotdale Gravel reflector
- Top of the Kowai Gravel (Kowai Formation) reflector
- Reflectors within the Mt Brown Formation
- Reflectors in Pre-Quaternary age lithologies
- Fault
- Stratal terminations
- ❷ General seismic facies within the Omihi Valley

Figure 5.12: Processed seismic section Omihi-6. Vertical exaggeration 1.5:1.

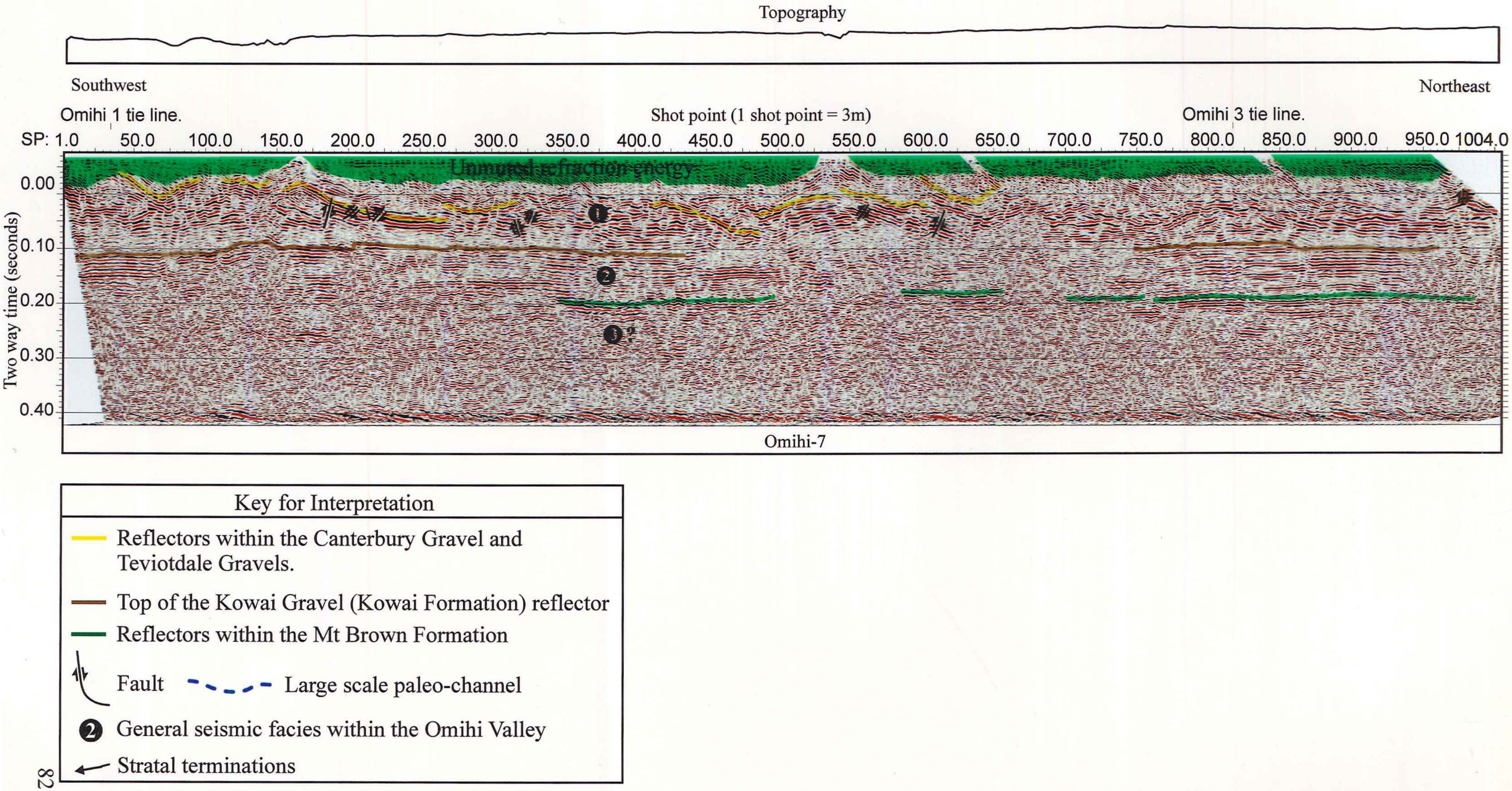


Figure 5.13: Processed seismic section Omihi-7. Vertical exaggeration 1.5:1.

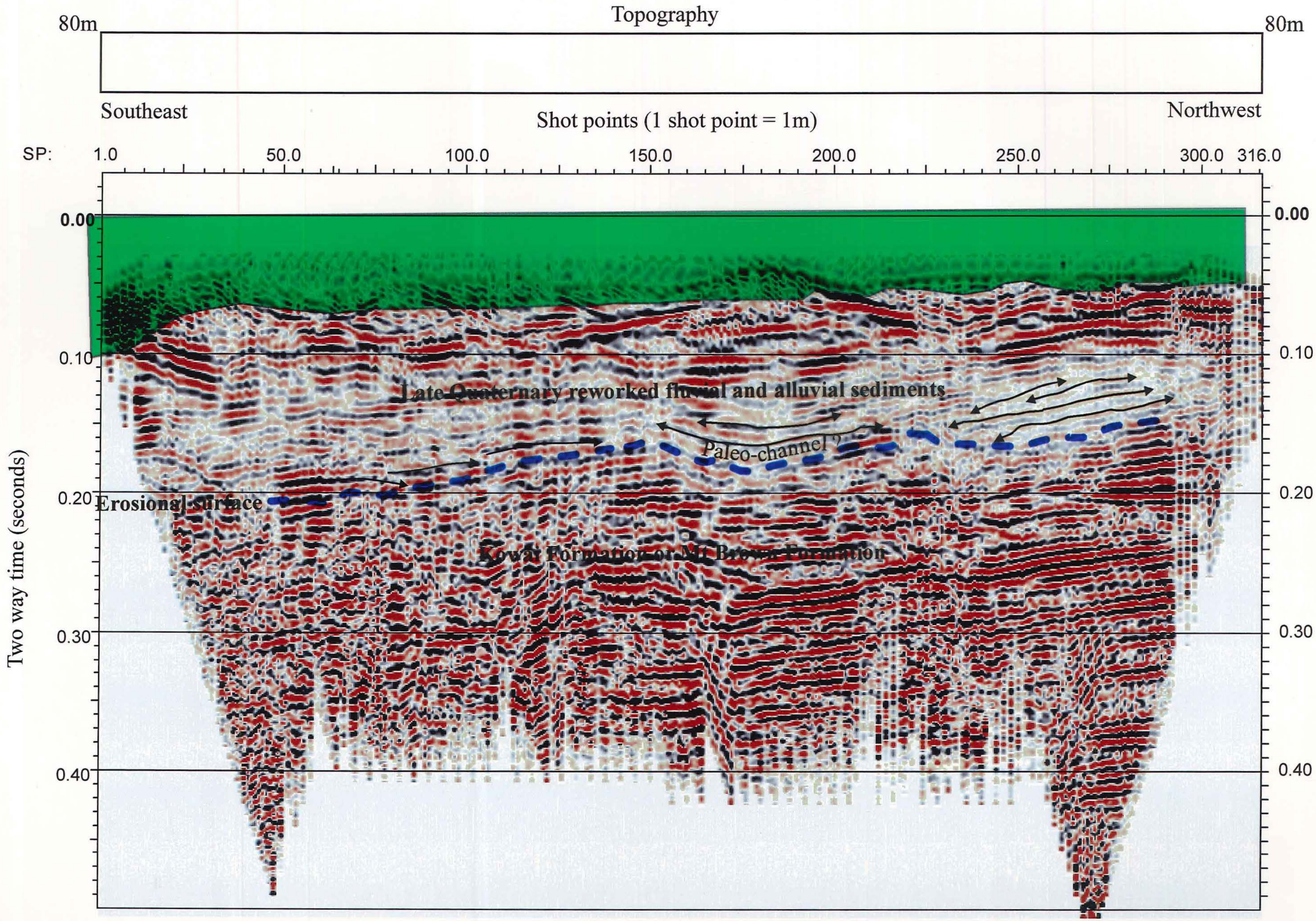


Figure 5.14: Processed high resolution seismic section Omihi-8. Vertical exaggeration 2:1.

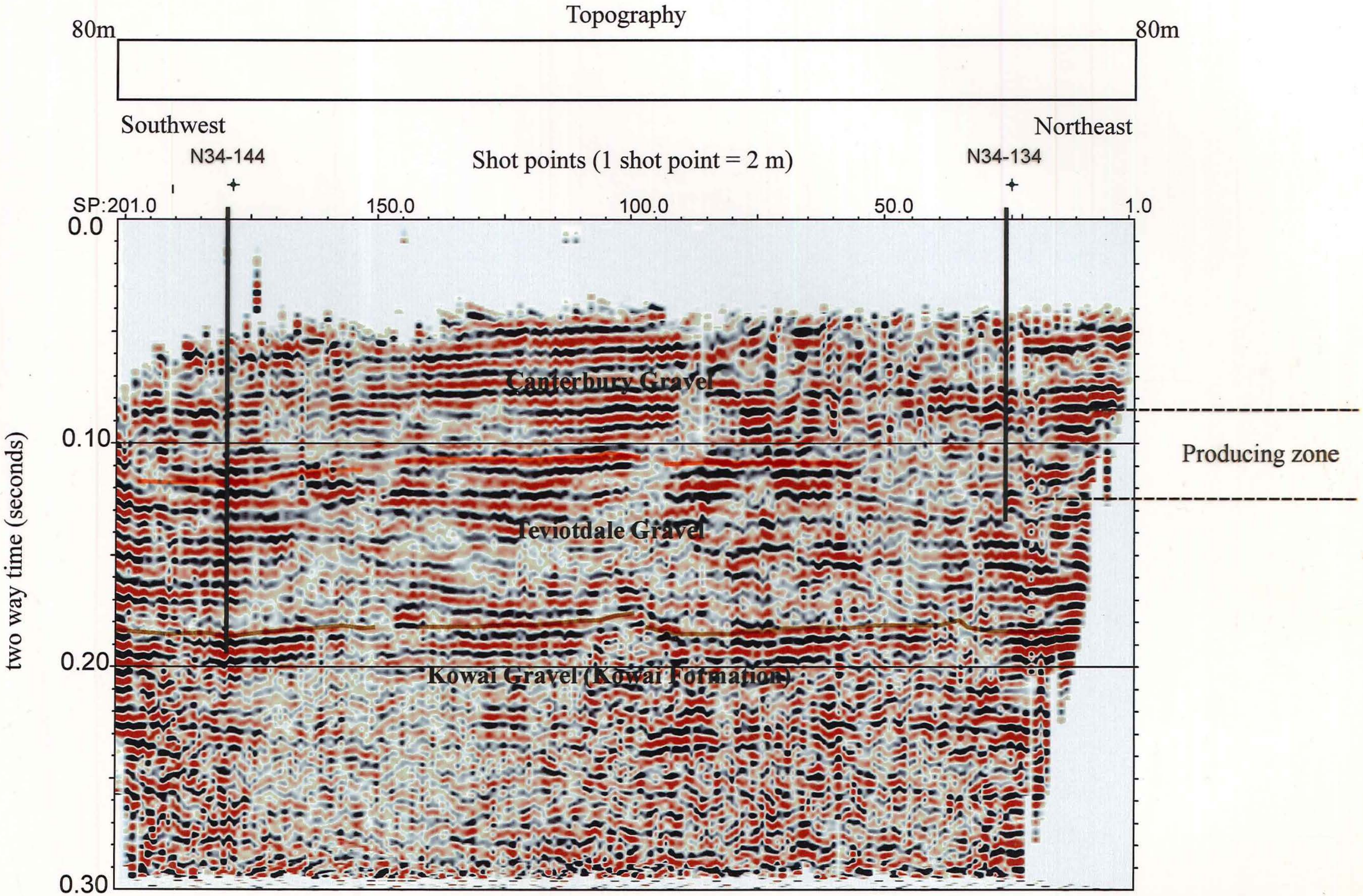


Figure 5.15: Seismic section showing high resolution seismic line Omihi-9 with borehole locations and depths shown.

5.6.Synthesis:

The geophysical and geological investigations undertaken have resulted in two main advances in the geological model for the Omihi Valley. Firstly, the large-scale structural form for the valley has been clearly defined and characterized. Secondly, the Late Quaternary sedimentary fill has been delineated and quantified in terms of lateral extent, depth and three dimensional architecture. The following synthesis of the data is divided into tectono-structural and sedimentary-fill components.

5.6.1. Structural synthesis:

The topographic expression of the valley is important in defining the Late Quaternary and ongoing deformation of the valley and surrounding hillslope terrain, and allows several inferences to be drawn:

5.6.1.1. Topographic expression of the Omihi Valley:

Topographically the Omihi Valley floor has not reached a steady-state. The valley is not a simple tectonically controlled space which has been sequentially filled with sediments as seen in more tectonically quiescent environments. The surrounding valley margins clearly show the high level of tectonic activity that has taken place in this area, and this activity is also depicted in the valley floor. The valley floor surface is inclined to the northwest, in the opposite direction to the underlying Pre-Quaternary and early Quaternary strata. The inclination of the valley floor decreases to the north. This topographic expression may be in response to several factors, including:

- The northern portion of the valley is an older surface and has had more time to reach equilibrium. This would imply that the north of the valley has been less tectonically active in the Late Quaternary.
- The Omihi Stream has less erosional power in the north of the valley and has not down cut into the underlying, older lithologies. This would suppose that the topographic expression of the valley floor is degradational. This is, however, thought to be unlikely, as the Omihi Stream and many other rivers and streams in north Canterbury are at present down-cutting into what is believed to be the post-glacial maximium surface.

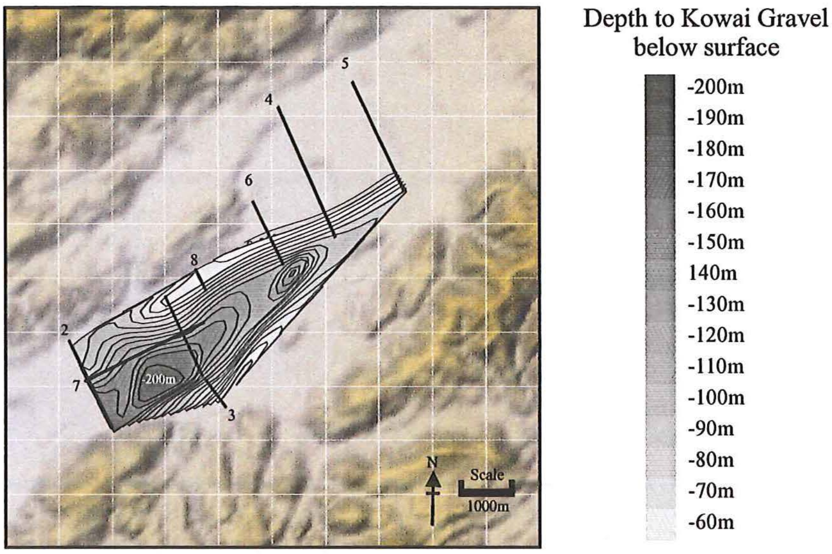
- The erosional sediment flux from the northwestern margin is greater in the north of the valley than the south. The sediment flux from both margins is therefore equal and results in a near horizontal valley floor.
- The northern part of the valley is less affected by footwall splays. The valley floor is therefore undergoing less deformation and is more horizontal.

The preferred scenario is that the present geometry of the valley represents a mixture of more active alluvial fan building on the southeast valley margin and active or recently active footwall splays of the Omihi fault causing ongoing deformation and uplift of the southeast valley margin.

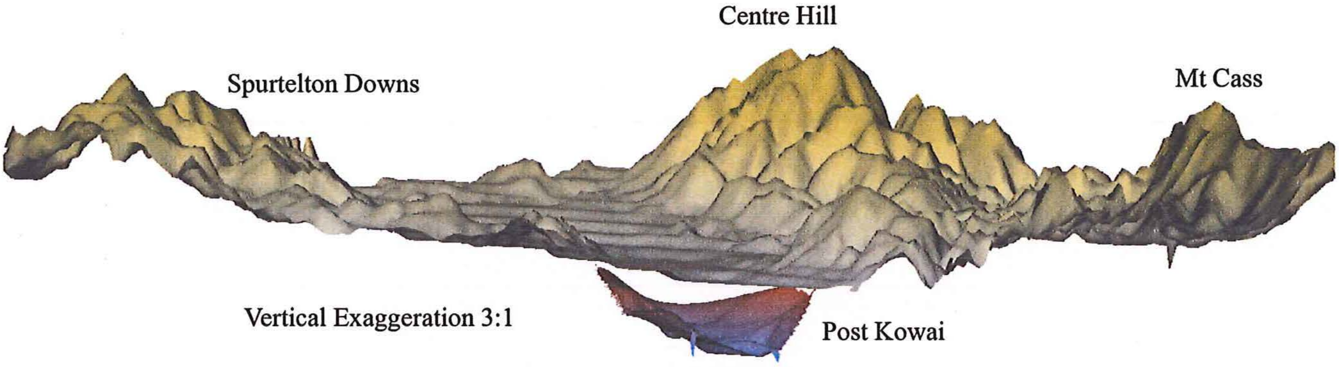
5.6.1.2. Structural geometry of the Omihi Valley:

The Omihi Valley appears to consist of two different fault controlled zones (Figure 5.16). In the southern half of the Valley, the thrust structure underlying the Black Anticline has undergone greater uplift resulting in an anticlinal structure and the breaking out of the fault to the surface (Figure 5.16 and Appendix 8 - Map 5). It is expected that further south of the Black Anticline, the gradually reducing amplitude of deformation will continue to be accommodated by folding. In the northern half of the valley, the Omihi Fault appears to split with one splay of the fault continuing at roughly the same strike, and a second splay stepping to the northwest over along the west margin of the northern Black Anticline. This segmented fault structure has previously been documented in north Canterbury (Yousif, 1988; Nicol et al., 1994). In this study no major fault splays are mapped based on geomorphic expression, and the new seismic data, but several minor fault splays are recognised on the seismic lines along the southeast valley margin. These faults are interpreted as footwall imbricate splays of the Omihi Fault system and may represent the initial stages in the development of a more complex imbricate rangefront fault system.

The segmented nature of the fault system within the valley has resulted in a complex subsurface valley geometry. In the south (seismic line Omihi-1) the Black Anticline thrust has overturned the strata along the southeastern valley margin, producing a southeastern dipping wedge of strata with minor footwall splays. In the centre of the valley the fault system appears to have undergone less deformation and the thrust appears to be less evolved, with limited surface geomorphic expression. This reduced deformation results in synclinal warping of the strata, but no overturning. It also results in only minor footwall splays being present on seismic reflection line Omihi-3. Further to the north the fault system appears to be more



(a): Structural contour map of the Post Kowai Syncline with seismic lines positions shown. Contour lines are in 10 m interval and show depth below ground surface to the Kowai seismic reflector.



(b): Three dimensional representation of the Post Kowai Syncline and Omihi Valley topography (viewing angle is from the southwest).

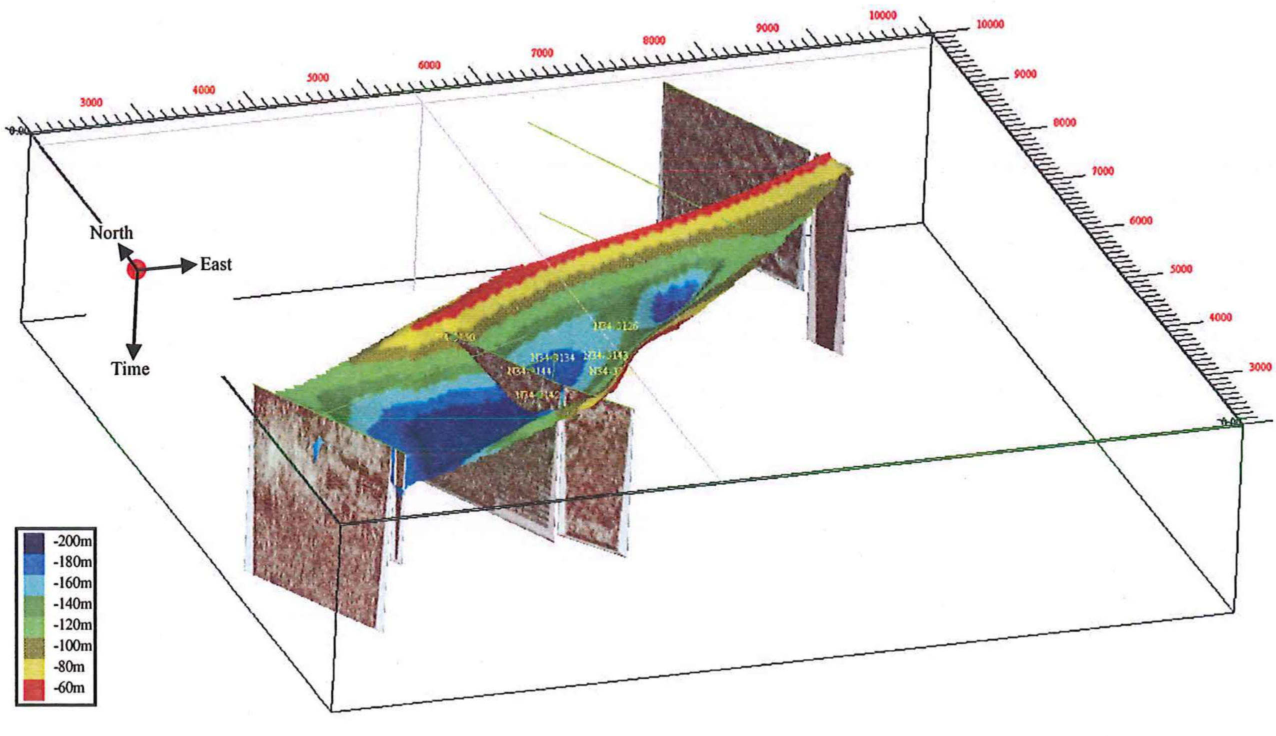


Figure 5.16: (c): Three dimensional representation of the Late Quaternary Valley fill syncline (Post-Kowai Gravel).

developed and has resulted in strong deformation of the strata forming what appears to be a more complex rangefront fault deformation, similar to that of the southern thrust fault.

The seismic reflection data also indicate that the formation of the valley and associated fault systems occurred after deposition of the Early to Mid Quaternary Kowai Formation and in particular after the Kowai Gravel were deposited. This is based on the Kowai Gravel and earlier formations having similar apparent dips and deformation where they are imaged in the northern seismic lines. The Late Quaternary fill that has been deposited within this syncline onlaps this Kowai Gravel.

Several key developmental stages of the Omihi Valley have been identified, these are:

- The Omihi Valley began forming in Early-mid Quaternary and continues to develop today.
- Initially the valley margins consisted of uplifted and deformed Kowai Formation Gravels. Ongoing and repeated cycles of eustatic sea-level changes resulted in repeat episodes of degradation and aggradation in the valley. Continued uplift exposed limestone, providing significant quantities of eroded limestone fine gravel clasts flooding into the valley.
- Uplift in the north of the valley has been greater than the south. In the valley floor the underlying Tertiary strata have been exposed, and are being eroded. The Tertiary lithologies are hetergenous and indurated, forming the dissected hillslope topography.

5.6.2. Synthesis of Late Quaternary valley fill data:

Seismic reflection results have defined the gross structural form of the Late Quaternary Omihi Valley fill. The nine reflection profiles show that the post-Kowai deposits are in the general form of a broad, open synclinal depression. This structure shallows to the northeast and the synclinal depression changes in the southwest of the valley into a deforming wedge (Figure 5.16 and 5.17). The following points can be determined from seismic and geologic mapping concerning the pre-and post-Kowai sedimentary fill:

- The post-Kowai syncline contains the majority of the valley Late Quaternary Gravels and sediments.

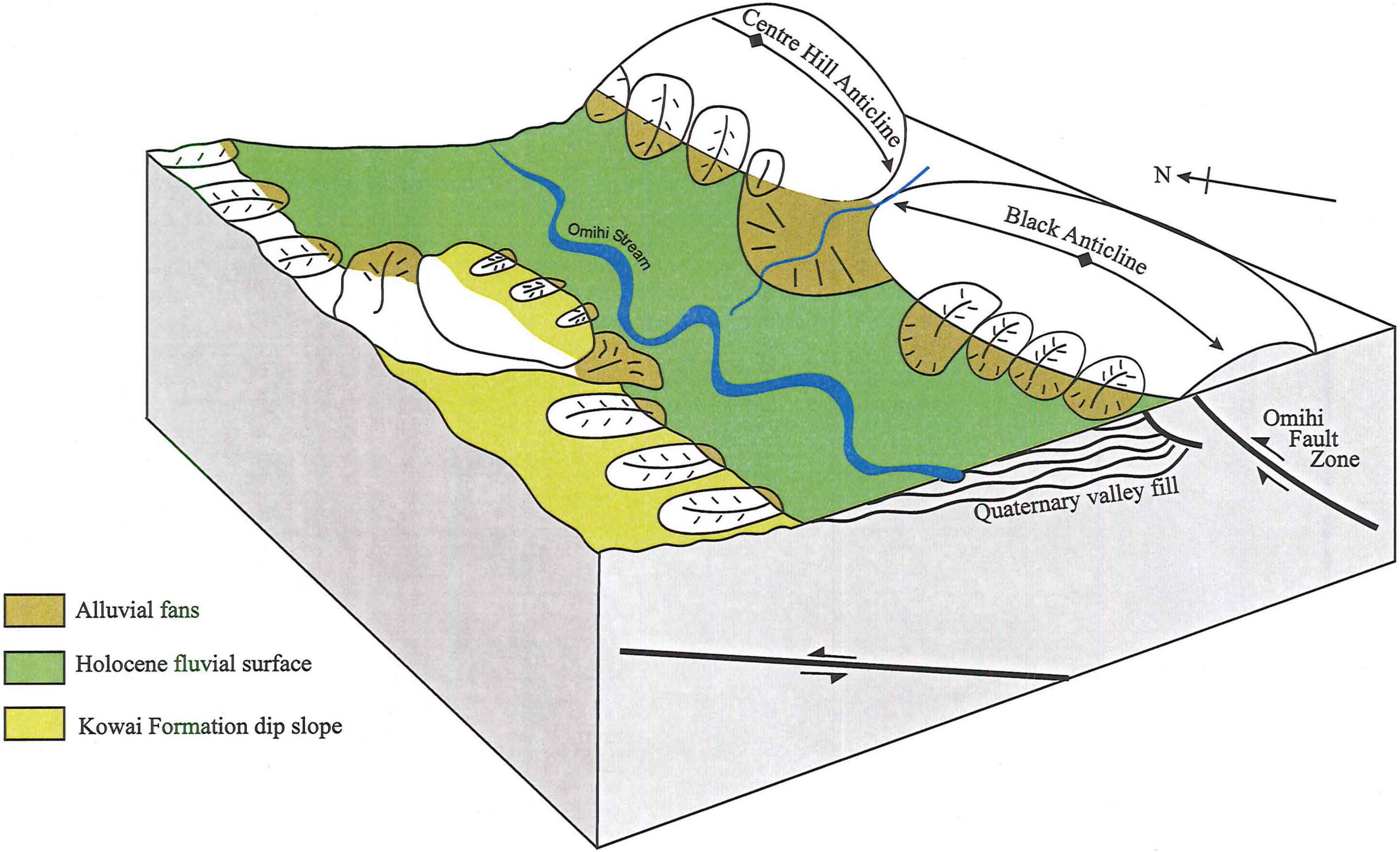


Figure 5.17 : Cartoon showing the present structural form of the Omihi Valley.

- Large-scale paleo-channels that have incised into the pre-Kowai and Kowai deposits on the western valley margin during repeated cycles of incision and deposition.
- Alluvial fans that have built out from both valley margins, and
- Possible paleo-channels that have incised into the Tertiary sediments in the north of the valley.

Borehole results indicate that the Teviotdale and Omihi Gravels within this syncline are of very variable composition. Boreholes on the eastern side of the valley show a high limestone and silt/clay content in the first 100 m. This material is inferred to have been formed by alluvial fans sourced from the uplifted eastern hillslope catchments of the valley building out over the valley floor. The probability of finding a producing aquifer within these alluvial fan deposits is small due to the very low permeability of the sediments. Below this alluvial fan material (at a depth of about 100 m) the valley fill becomes less clay bound with a higher percentage of sand/silt matrix, and accompanied by increased permeability. This material continues with changes in lithology until what is believed to be, the Kowai Gravel (Kowai Formation) is encountered at 188 m. The Kowai Gravel at the one location where it was drilled showed that it was clay bound and not a good potential water resource, but care should be taken when extrapolating from this one result, to all of the Kowai Gravels present in the valley. It is known from surface outcrop of the Kowai Gravels elsewhere in Canterbury, that they are highly variable in character and may change from clay bound gravels to mainly sand and sandy gravel horizons over deci-metre distances. It appears from the information presently available that the main hydrological resource is the horizon underlying the alluvial fan derived material and above the clay bound Kowai Gravels. Though the southeastern margin of the valley contains the greatest thickness of this material it also appears to be the most active tectonically. This implies that the material closest to the eastern margin may be the most affected by structural dislocation, as well as formation of the alluvial fans and the succession may in fact be totally silt/clay bound over its full depth. This zone is a poor water prospect and would be unlikely to contain any good producing aquifers. At present, it is not possible to determine this definitively as no deep wells have been drilled close to the south-eastern margin. The exception is well N34-282, at Spye Farm to the north. The samples recovered from this well appear to consist of alluvial fan derived material to a depth of 170 m and the well is a poor producer (<5 l/s).

On the western side of the valley, the post-Kowai material becomes progressively thinner until the Kowai Gravels outcrop on the western margin forming the valley flank. The seismic data shows that the post-Kowai history along this side of the valley is more complicated than the eastern side, with large-scale paleo-channels and what appear to be large-scale, cut and fill paleo-river terraces and fans (Figure 5.13). From the seismic profiles it appears that the Omihi River and the paleo-Omihi have been located along the western margin of the valley throughout most of the Late Quaternary. This would imply that the present westerly dip of the Omihi Valley surface has been maintained over that period, deflecting the Omihi and paleo-Omihi to the west margin. The paleo-Omihi River appears to have cut down into the underlying Kowai Gravels on this west margin and deposited new material. This new material, if clean, could be a potential aquifer horizon and provides a potential groundwater resource target.

To the north of the valley the thickness of the Late Quaternary deposits gradually thins. The Kowai syncline continues its northeastern trend but diminishes in both wavelength and amplitude. Overall the near surface materials present do not offer a very high probability of containing good producing aquifers as it mainly consists of Tertiary sandstones/mudstones. However, several paleo-channels that have incised into the Tertiary sequence may offer a possible resource for future exploration and exploitation.

Chapter 6. High Resolution Seismic Reflection Characterisation of Producing and Non-producing Wells

6.1. Introduction:

Alluvial and fluvial aquifer systems are, by nature, heterogeneous and complex (Best and Bristow, 1993; Browne and Naish, 2003). The accuracy and usefulness of hydrological models which represent the three dimensional distribution of porosity and permeability would be improved if a non-invasive, rapid method, with a dense sampling interval was available for directly or indirectly characterizing the subsurface distribution of those parameters. Information such as aquifer and aquitard distribution, size and interconnectivity could then be obtained from such a method allowing economic aquifer units to be identified and targeted by drilling. This chapter describes work undertaken to evaluate if shallow high resolution P-wave seismic reflection surveying could delineate such hydrological subsurface properties in the Omihi Valley using two different approaches. The first is the delineation of subsurface sedimentary architecture such as paleo-channels which are believed to be associated with high porosity/permeability units (aquifers) in the Omihi Valley this method uses pre-defined geologic and hydrologic models to indirectly link the seismic reflection image to aquifer units. The second method uses an attribute of the seismic data, interval velocity to identify aquifer and aquitard units directly.

While extensive work has been undertaken characterizing lithology and rock parameters using seismic reflection methods for hydrocarbon exploration, (Walls et al., 2002) much less work has been done to assess the effectiveness of using shallow seismic reflection surveying to improve the subsurface characterization of key hydrological properties (Rubin et al., 1992; Baker et al., 2000; Bachrach and Mukerji, 2001). Hydrological subsurface characterization is usually achieved by the use of geostatisical analysis of a limited number of boreholes, and outcrop information (Fetter, 2001).

6.2. Aims:

A single seismic line, Omihi-9, has already been undertaken to investigate the difference in subsurface seismic character between a producing (N34-139) and non-producing well (N34-144) (Figure 5.15). This limited survey indicated that seismic character differences are present between the producing and non-producing horizons (see chapter 5 of this thesis). The Omihi-9 survey was a single line which resulted in structures being imaged in only two dimensions. The survey parameters such as shot-receiver offsets and shot spacing were not optimum for the survey aims. It was therefore decided that further seismic reflection surveys would need to be undertaken with the specific aims of:

i) delineating the three-dimensional, small-scale, paleo-fluvial and fault features within the subsurface; in particular to image paleo-channel features which are believed to contain the economically important aquifers within the Omihi Valley; and

ii) determining if P-wave seismic reflection surveying would be successful in characterizing subsurface parameters including porosity, permeability, fluid saturation and silt/clay content within the Late Quaternary sediments.

To be able to meet the above aims, the acquisition parameters for these new, high resolution surveys were tailored to enhance the lateral and vertical resolution of the surveys, increase the useful fold of coverage between 0-150 m and to increase the accuracy of the shallow velocity model (0-150 m) (see Appendix 6 for details).

6.3. Methodology:

6.3.1. Seismic reflection surveys:

The experiment consisted of two sets of two dimensional seismic reflection lines centred around a logged producing well and a non-producing borehole. This allowed two differing hydrological regimes to be compared and contrasted using the seismic reflection method.
The two high-resolution seismic surveys undertaken are located adjacent to a producing well (N34-139) and a non-producing borehole (N34-144) (Appendix 8 – Map 1). (Well N34-134 which is adjacent to the Omihi-9 seismic line is not suitable for the high resolution surveys as it is located near the main farm homestead and farm buildings which are in constant use).
Well N34-139 has a flow rate of 350 l/minute from screen zones at 90-100 m (Loris, 2000) and borehole N34-144 (if screened over all producing horizons) has an estimated flow rate of

<300 l/minute (pers. comm. McMillan Drilling Ltd 2002). Due to economic reasons the second borehole (N34-144), with an uneconomic production rate did not warrant further development and the casing was pulled after drilling.

Four seismic lines, with two different geometries, where undertaken around each of the two locations (Figures 6.1, 6.2 and 6.3). The survey geometry around borehole N34-144 consisted of four lines defining a square, with an overlap of 48 m at each corner. This geometry was chosen as several large stands of trees were located near the well and this geometry minimises the length of seismic line passing through them. The survey geometry around well N34-139 was a set of four parallel lines located perpendicular to the down valley axis (north-south). This geometry was selected after discussions with Professor Alan Green, ETH-Zurich, a leading practitioner of the shallow seismic reflection method. The geometry used has been successful in similar environments in Switzerland, where it delineated detailed three-dimensional structure, in similar unconsolidated glacial/fluvial sediments (Lanz et al., 1996; van der Veen et al., 2001). The more open environment around well N34-139 also lent itself to this geometry being chosen.

6.3.2. Borehole and Well logs:

Well N34-139 was logged by the farm owner (Peter Yewdall) and the drilling company (McMillan Drilling Ltd) and the well log produced by Environment Canterbury is included here as Figure 6.4. Borehole N34-144 was carefully logged and sampled during drilling by the author and J.Pettinga and A.Wandres and the methodology and results are included in Appendix 7 (Figure 6.5).

6.3.3. Survey Geometry and Acquisition Parameters:

The two surveys (Omihi-UHR-1 and Omihi-UHR-2) were undertaken one month apart. The initial intention was to undertake survey Omihi-UHR-1 using a seismic shot gun source, but this proved impossible due to mechanical firing problems. Therefore the survey was conducted using a hammer and plate source with a single stack, and then a section of Omihi-UHR-1D was repeated using the seismic pipe gun source (Omihi-UHR-1D-2). Survey Omihi-UHR-2 (A-D) was shot using the seismic pipe gun source for all shots.

The survey geometries used are shown in Figures 6.1 - 6.3. The acquisition parameters used for the two surveys are shown in Table 6.1 - Table 6.4. Topographic elevation changes for Omihi-UHR-1 and Omihi-UHR-2 are less than 1 m and were further minimized by careful depth control of source shots for survey Omihi-UHR-2. Survey shot and receiver locations were measured using a mixture of differential GPS surveying and measuring tape (accuracy +/- 10 cm).

Table 6.1 Acquisition Parameters for Omihi-UHR-1A,1B	
Source type	10 Kg Hammer and plate, single impact
Source point minimum offset	0 m
Source point maximum offset	192 m
Shot points	96
Geophone type	3 series geophones, grouped, inline, 30 Hz Mark Products
Geophone group interval	4 m
Source interval	4 m
Shooting spread	48 channels (Push with no shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000 Hz) 1 second

Table 6.2 Acquisition Parameters for Omihi-UHR-1C,1D	
Source type	10 Kg Hammer and plate, single impact
Source point minimum offset	0 m
Source point maximum offset	192 m
Shot points	96
Geophone type	3 series geophones, grouped, inline, 30 Hz Mark Products
Geophone group interval	4 m
Source interval	4 m
Shooting spread	48 Channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000 Hz) 1 second

Table 6.3 Acquisition Parameters for Omihi-UHR-1D-2	
Source type	Seismic pipe gun, single 12-gauge blank shell
Source point minimum offset	0 m
Source point maximum offset	192 m
Shot points	48
Geophone type	3 series geophones, grouped, inline, 30 Hz Mark Products
Geophone group interval	4 m
Source interval	4 m
Shooting spread	48 Channels (Push with no shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000 Hz) 1 second

Table 6.4 Acquisition Parameters for Omihi-UHR-2A,2B,2C,2D	
Source type	Seismic pipe gun, single 12-gauge blank shell
Source point minimum offset	0 m
Source point maximum offset	192 m
Shot points	96
Geophone type	3 series geophones, grouped, inline, 30 Hz Mark Products
Geophone group interval	4 m
Shooting spread	48 Channels (shoot through)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000 Hz) 1 second

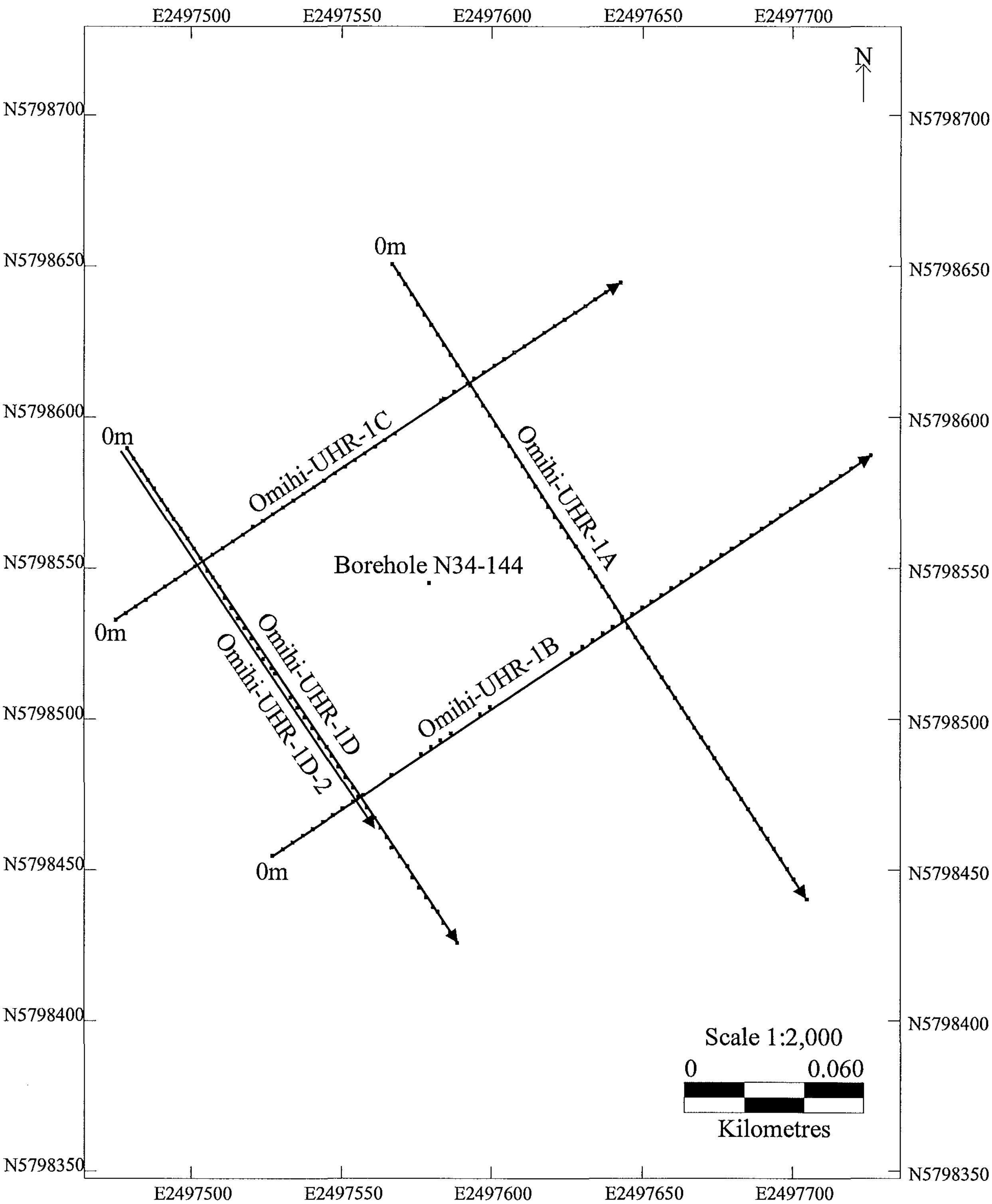


Figure 6.1: Location of Omihi-UHR-1A,1B,1C,1D and 1D-2 high resolution seismic reflection lines. (New Zealand Map Grid NZMG 260).

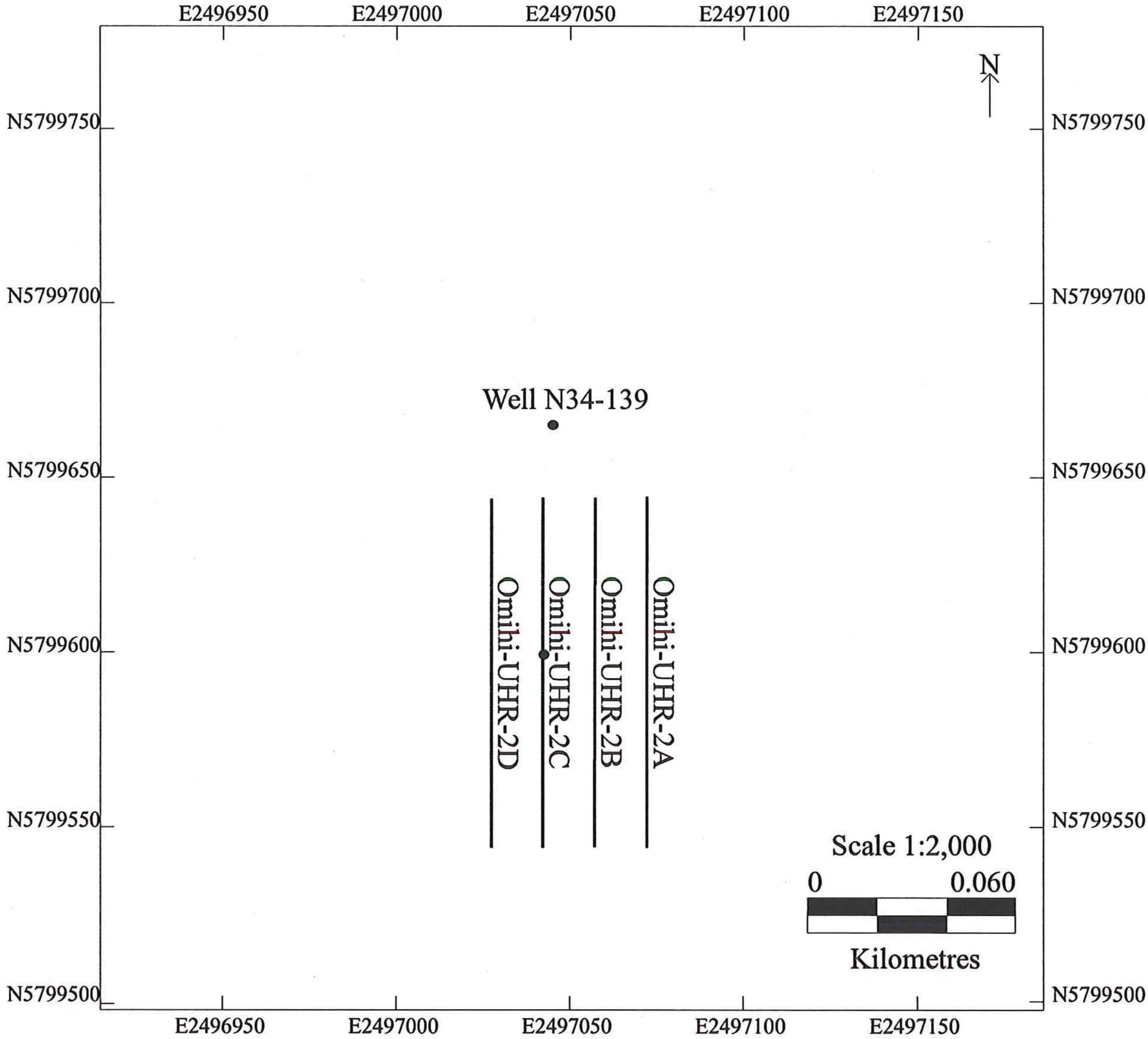


Figure 6.2: Location of Omihi-UHR-2A, 2B, 2C, 2D high resolution seismic reflection lines. (New Zealand Map Grid NZMG 260).

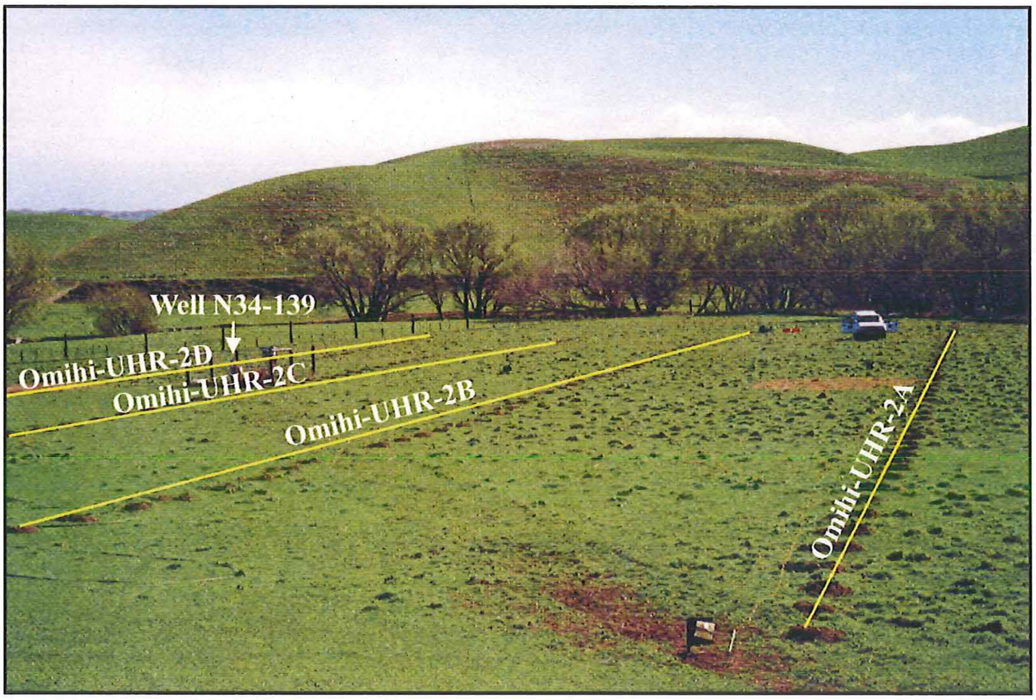


Figure 6.3: Photograph looking northwest of UHR-2 site survey location showing four parallel survey lines (Omihi-UHR-2A, 2B, 2C, 2D).

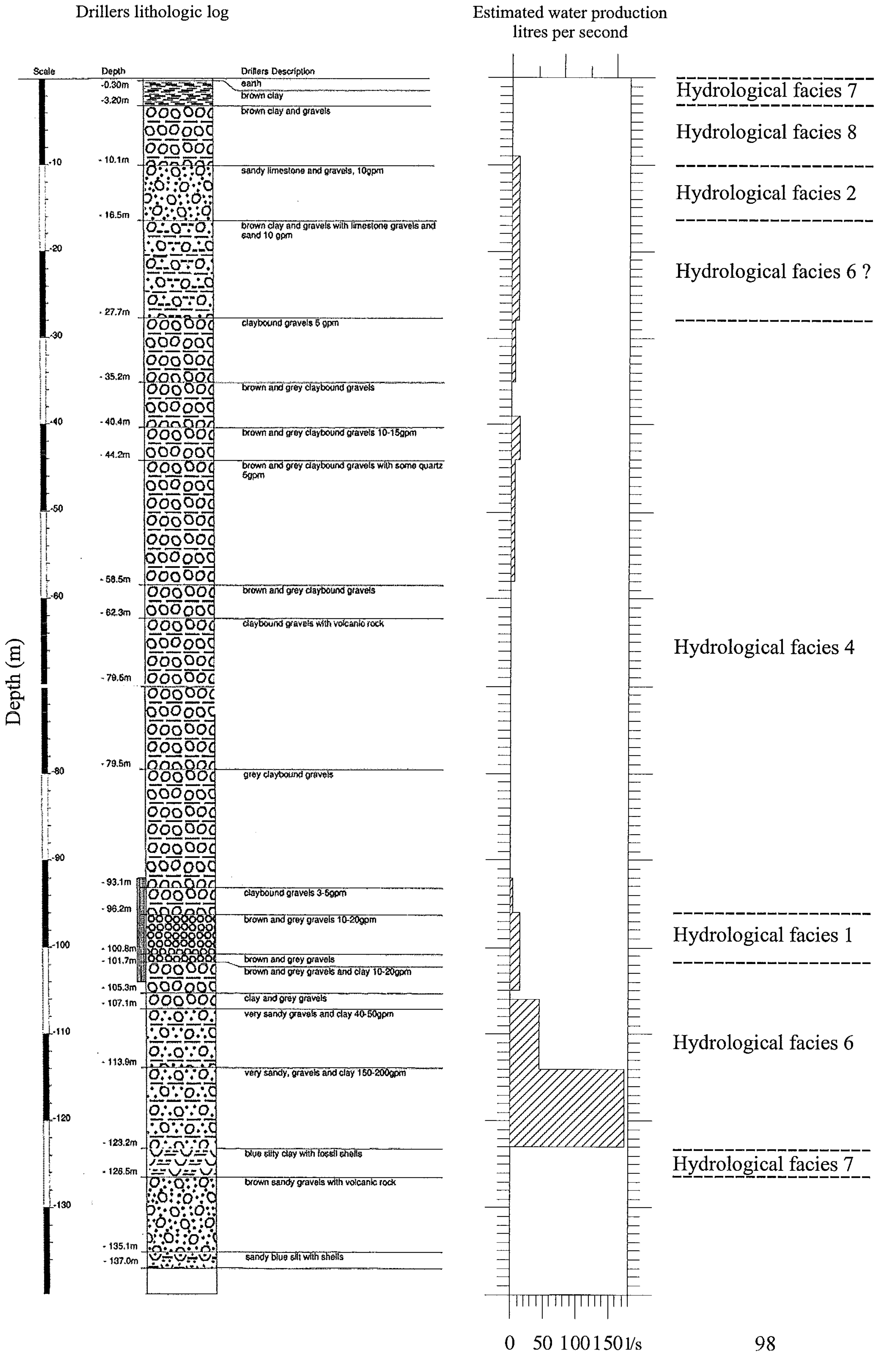


Figure 6.4: Well N34-139 division into hydrological facies.

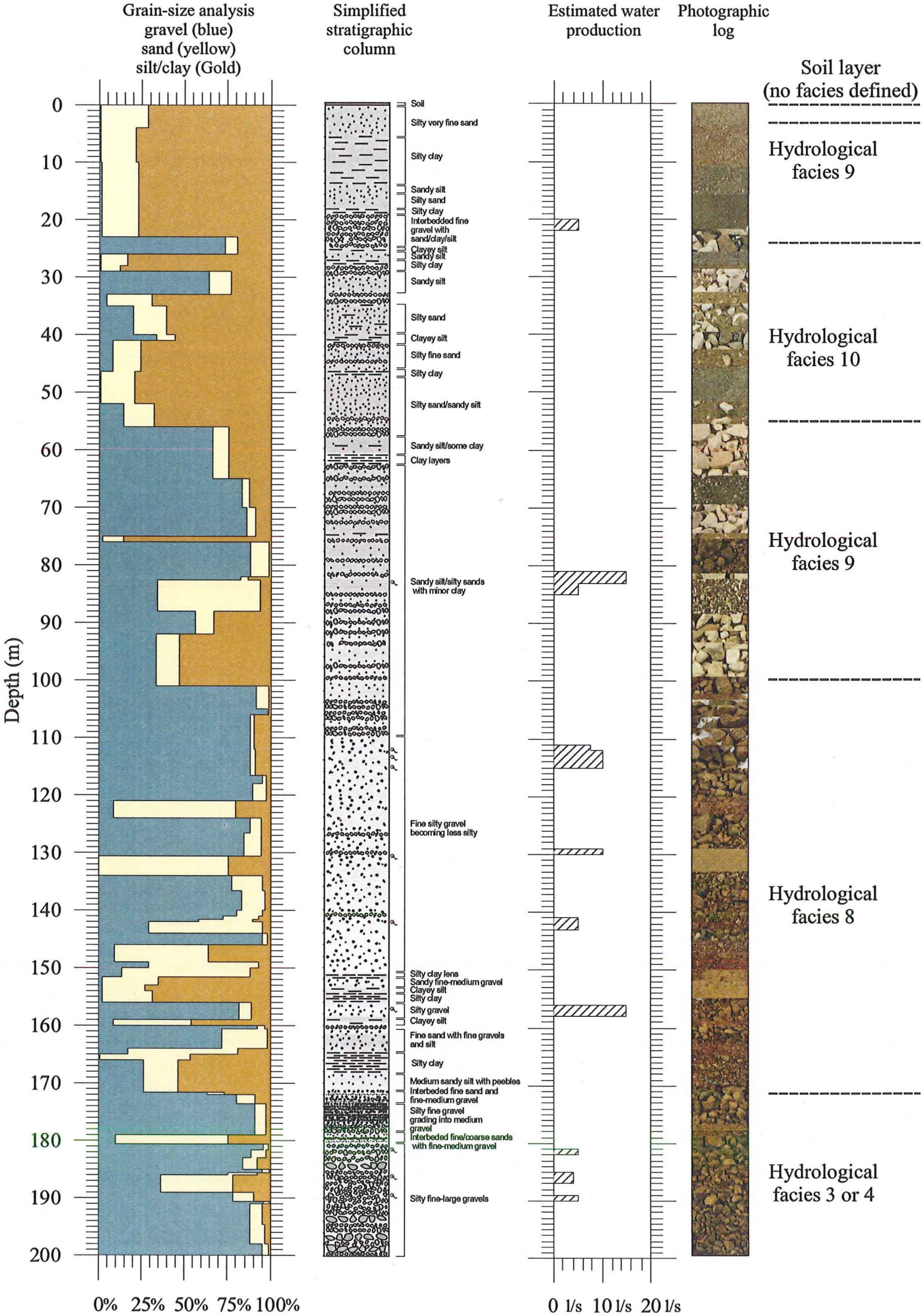


Figure 6.5: Borehole N34-144 division into hydrological units, and associated hydrological facies.

6.3.4. Survey resolution:

The bandwidth advantages of the seismic pipe gun (SPG) source over the hammer and plate source can be seen in Figure 6.6. Both the hammer and plate and SPG have usable frequencies up to 200 Hz, but the amplitude spectrum for the SPG source shows a greater percentage of its energy at high frequencies especially in the 100-200 Hz range. Using 200 Hz as the maximium frequency of the source wavelet gives a vertical resolution of 2.5 m using an average interval velocity of 2000 m/s (1/4 wavelength criteria) and a lateral resolution at 100m deep using the fresnel zone criteria, of 20 m (Yilmaz and Doherty, 1987).

6.4. Processing:

The key aim of the surveys was to obtain the highest lateral and vertical resolution image of the subsurface. This requires the generation of a high frequency source wavelet. Processing is therefore optimized to retain the high frequency P-wave component of the seismic wavefield. Standard shallow seismic processing was applied to the data (Appendix 6), and due to the high ambient environmental and cultural noise around borehole N34-144, very careful muting and trace editing was applied to this data set. The processing flow used is shown in Table 6.5.

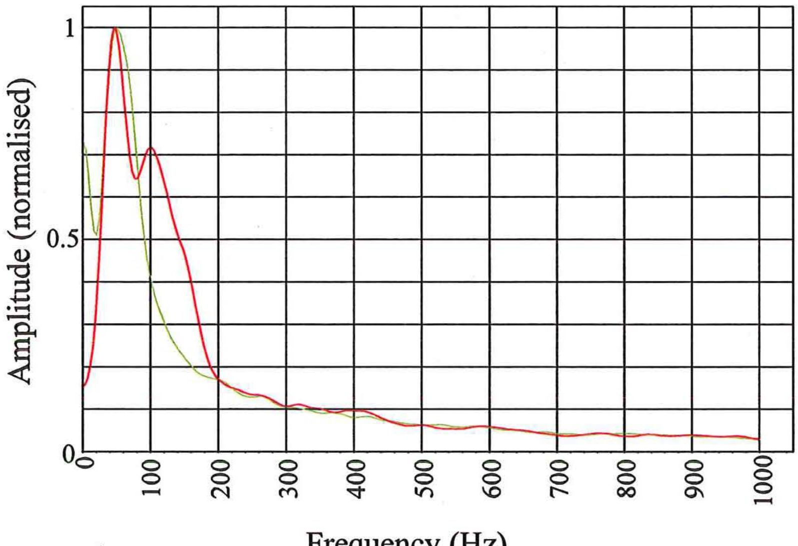
Table 6.5

Processing Flow

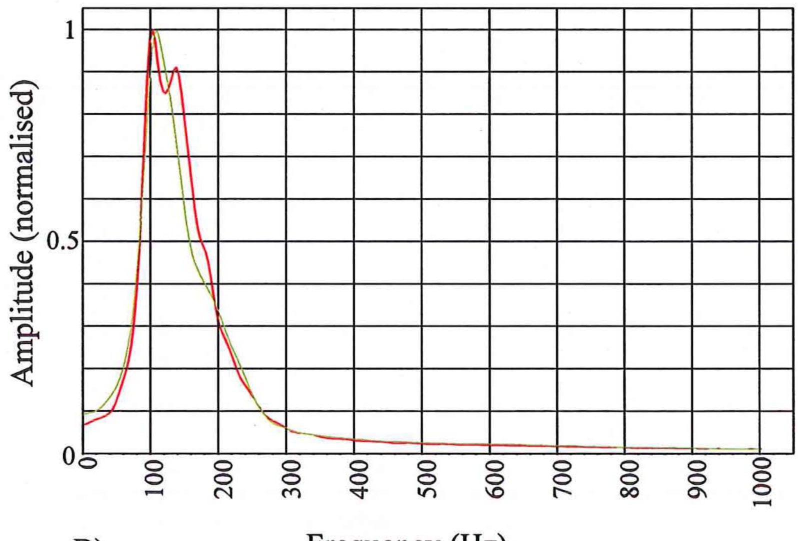
⇩

Convert SEG-2 to SU Format
*Window 0-0.25s 0.25 ms sample rate (0.01-0.26)
Geometry
Kill bad traces
Filter 80-120-300-400 agc 50ms
Decon (use SUCOR to find wavelength)
Mute -90m-0-90m
AGC (balance trace by RMS average and 50ms)
Mute -90-0-90m
CMP Sort
NMO (using velocity model from refraction and semblance and CVS)
Residual statics (2 ms maximum shift)
Stack
AGC 50 ms
Trace addition -0.5, 1, -0.5

*A 0-0.25 s window was chosen as it encompasses the total drilled depth of 200 m with a small margin of error.



A)



B)

Figure 6.6: (A) Frequency spectrum of shot gathers for Omihi-UHR-1D (hammer source-green) and Omihi-UHR-1D-2 (seismic shot gun source-red); (B) Frequency spectrum for final stacked sections for Omihi-UHR-1D (hammer source-green) and Omihi-UHR-1D-2 (seismic shot gun source-red). The seismic gun source has a greater percentage of its energy in the 100-200 Hz band, than the hammer and plate source. Both sources show useful energy up to 300 Hz.

Processing of seismic reflection data for detailed velocity and complex attribute analysis requires an in-depth understanding of the effect of processing stages on the final attributes. The processing undertaken for this thesis concentrated on inversion, envelope, instantaneous phase, and the interval velocity. Amplitude Versus Offset (AVO) analysis was not attempted on the data as it requires specially tailored field acquisition parameters and calibrated recording equipment (Brouwer, 1998; Russell et al., 2003).

6.5. Results:

The initial processing of the two surveys resulted in a seismic-stratigraphic image of the subsurface. To correctly interpret this image the section was converted from two-way time to depth using a carefully defined velocity model.

6.5.1. Velocity model:

The correct velocity model for the subsurface is important, so that the CMP gathers can be correctly stacked and also so that the two-way time seismic sections can be correctly converted to depth for interpretation.

A velocity model for the seismic profiles was defined using all available velocity information. The near surface surficial layer is defined using standard first arrival refraction interpretation (Redpath, 1973). Deeper RMS stacking velocities are defined using semblance and constant velocity stacks and converted into interval velocities using Dix's Equation. The accuracy of depths derived from NMO velocities is dependent on the geometry of the source-reflector-receiver raypath, the lateral heterogeneity of the subsurface, the dip of the reflector interfaces and other parameters. The stated percentage error in the accuracy of time-depth conversion is usually 10 - 20%.

Refraction processing, using manually picked first arrivals indicates a simple two-layer model for the near-surface (< 6 m). Forward and reverse shots were used to determine that there was only minor dip present on the near-surface layers.

Refraction calculations show that the first seismic-stratagraphic horizon is the unsaturated vadose zone, which is 2.8 m thick adjacent to well N34-139 and 3 m thick adjacent to N43-

144. This unsaturated zone has a velocity of 340-400 m/s. Below the unsaturated zone well N34-139 and borehole N34-144 have a layer with a velocity of >1600 m/s which is assumed to be the fully saturated (>98%) equivalent of the water table.

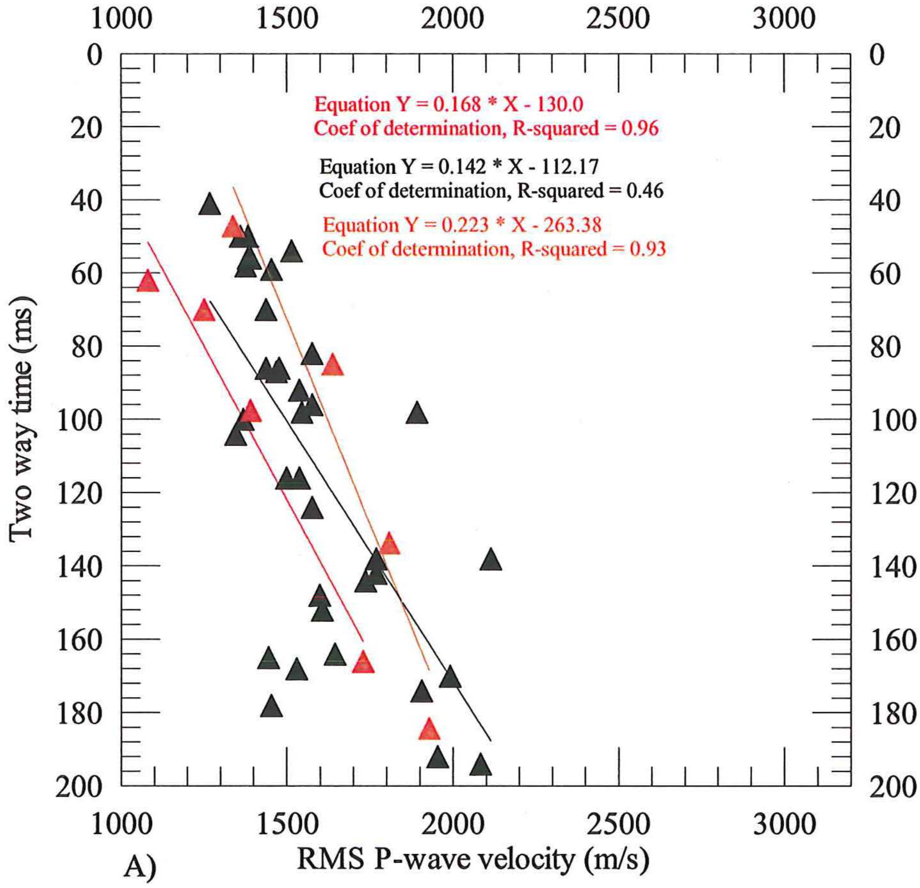
The velocity model below the vadose zone surficial layer indicates a general linear increase in velocity with depth. The velocity models for well N34-139 and borehole N34-144 are shown in Figure 6.7a and 6.7b. As can be seen from the two graphs, the subsurface velocities near borehole N34-144 increase less rapidly than those adjacent to well N34-139. Well N34-139 also shows a rapid increase in velocity between 100-120 ms TWT.

As a check on the semblance-derived velocity model, a second independent method was applied for borehole N34-144. A super-gather of the 25 shot gathers was produced using Omihi-UHR-1D-2 and Omihi-9 shot gathers, and the velocity vs. TWT calculated using the normal moveout reflection hyperbolas (Figure 6.8). This generated an independent velocity vs. TWT profile (Figure 6.7a red line and orange line). The two derived velocity vs. TWT models appear to be within the scatter of the data. The difference in the velocity model between N34-139 and N34-144 is interpreted to be directly related to the changes in lithology seen in the two borehole logs. The seismic surveys in the middle of the valley (near N34-144) penetrate a thick sequence (> 200 m) of unconsolidated gravel/silt/clay sediments while the survey adjacent to the valley margin (near N34-139) penetrates more sandy (only minor clay/silt) and fossiliferous sediments with minor volcanic derived clasts.

Two-way time seismic sections with the depths of important horizons marked are shown in Figures 6.9 and 6.10. The processed sections were then imported into a three dimensional-interpretation package (Kingdom Suite©) and placed in their correct geospatial position. The three-dimensional seismic-stratigraphic sections for borehole N34-144 and well N34-139 are shown in Figures 6.11 and 6.12. The instantaneous phase, envelope and inversion sections are presented in the CDROM in Box 1.

6.5.2. Measured and estimated production rates:

The Omihi aquifer system is consists of several different confined aquifer units. Water wells penetrate these confined aquifer units and have production screens located across the aquifer depth range. The screens therefore represent an estimate of the units containing the most permeable saturated horizons. The drillers log also indicates the estimated production for



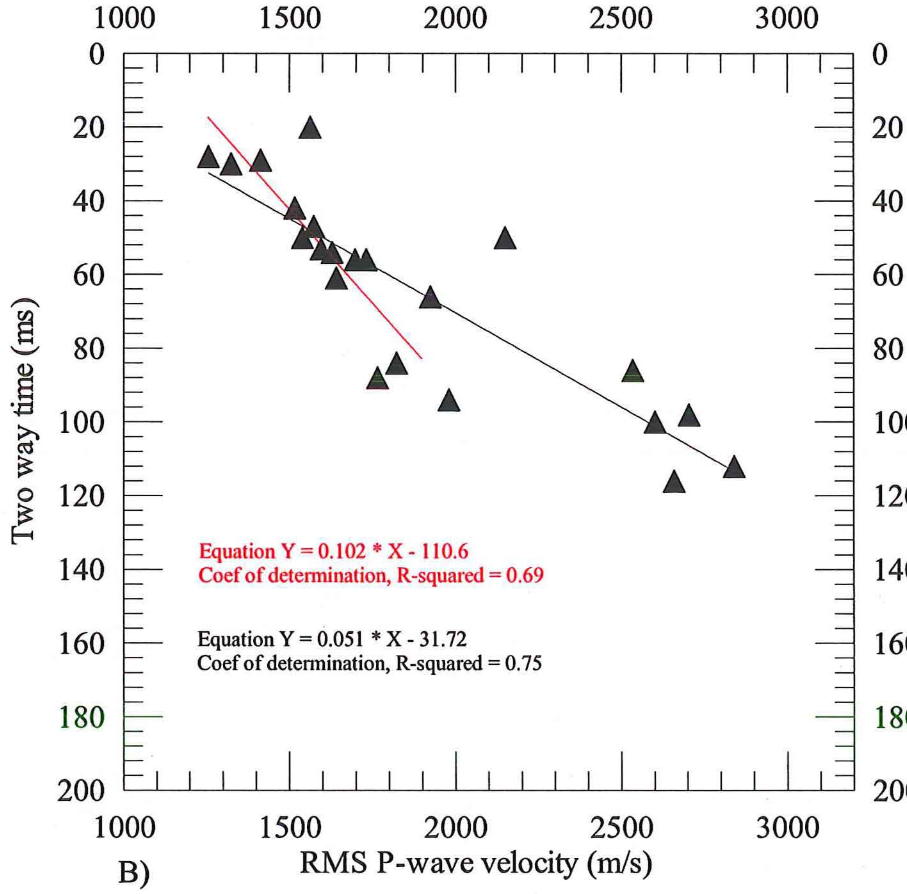


Figure 6.7: (A) Root mean square (stacking) velocity model adjacent to borehole N34-144 versus two way time (ms); (B) Root mean square (stacking) velocity model adjacent to well N34-139 versus two way time (ms).

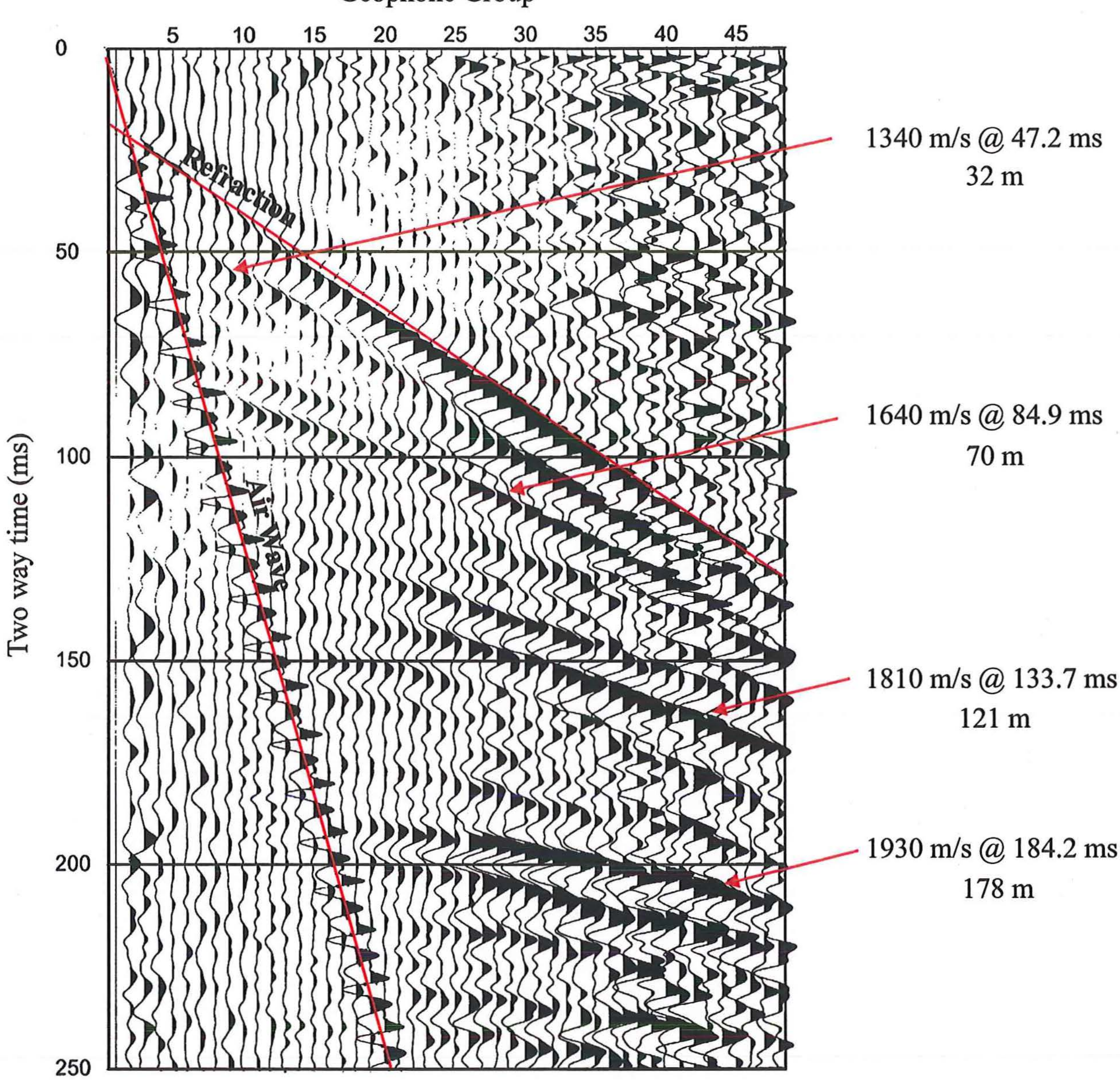


Figure 6.8: A super shot gather of the 25 shot gathers from Omihi-UHR-1D-2 showing RMS velocity vs. TWT calculated using the normal moveout reflection hyperbolas.

Omihi-UHR -1D-2

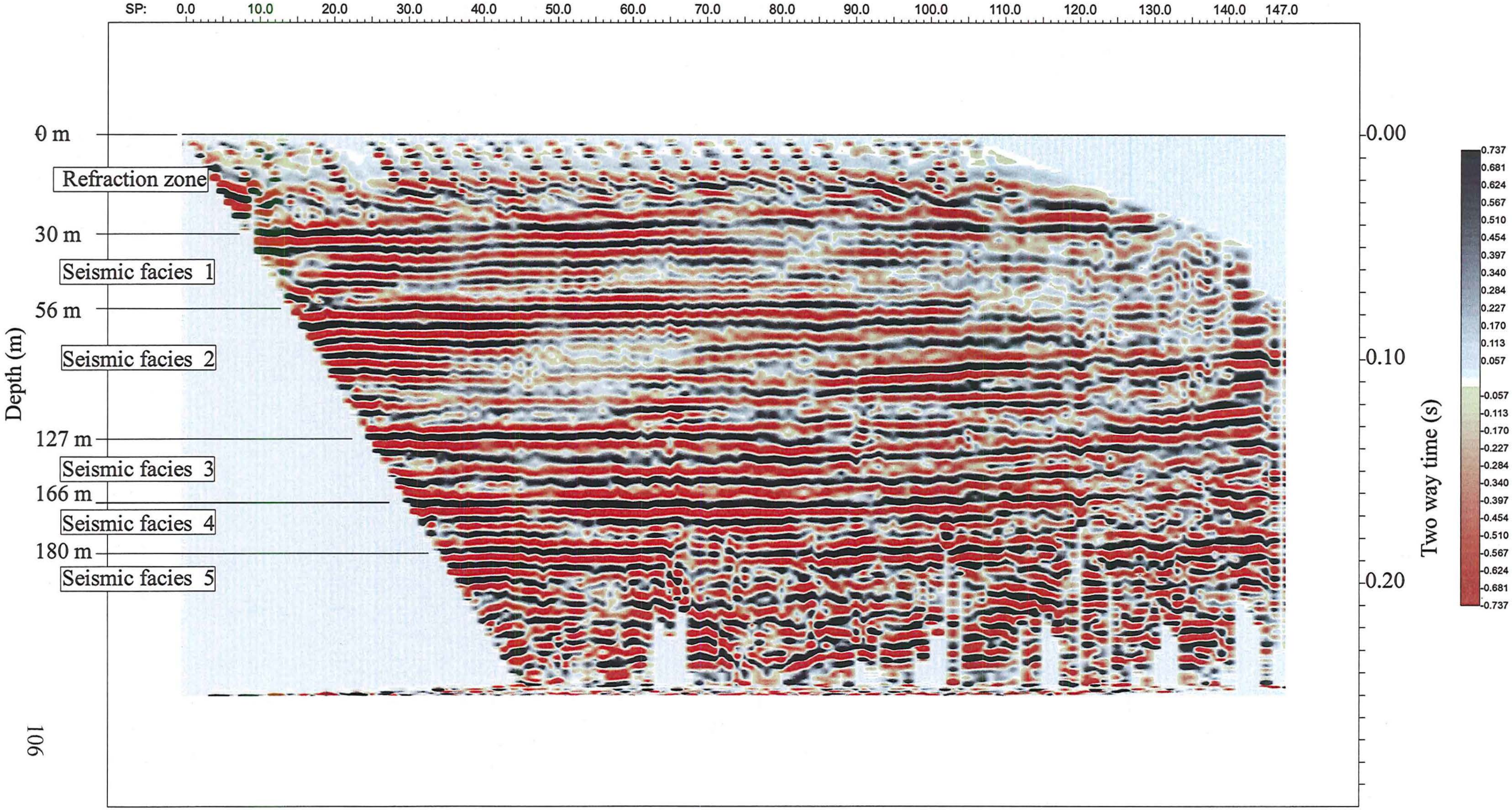


Figure 6.9: Seismic section Omihi-UHR-1D-2 showing main reflection horizons in two way time and depth in metres with main seismic facies shown. Depth conversion uses the velocity model shown in Figure 6.7A.

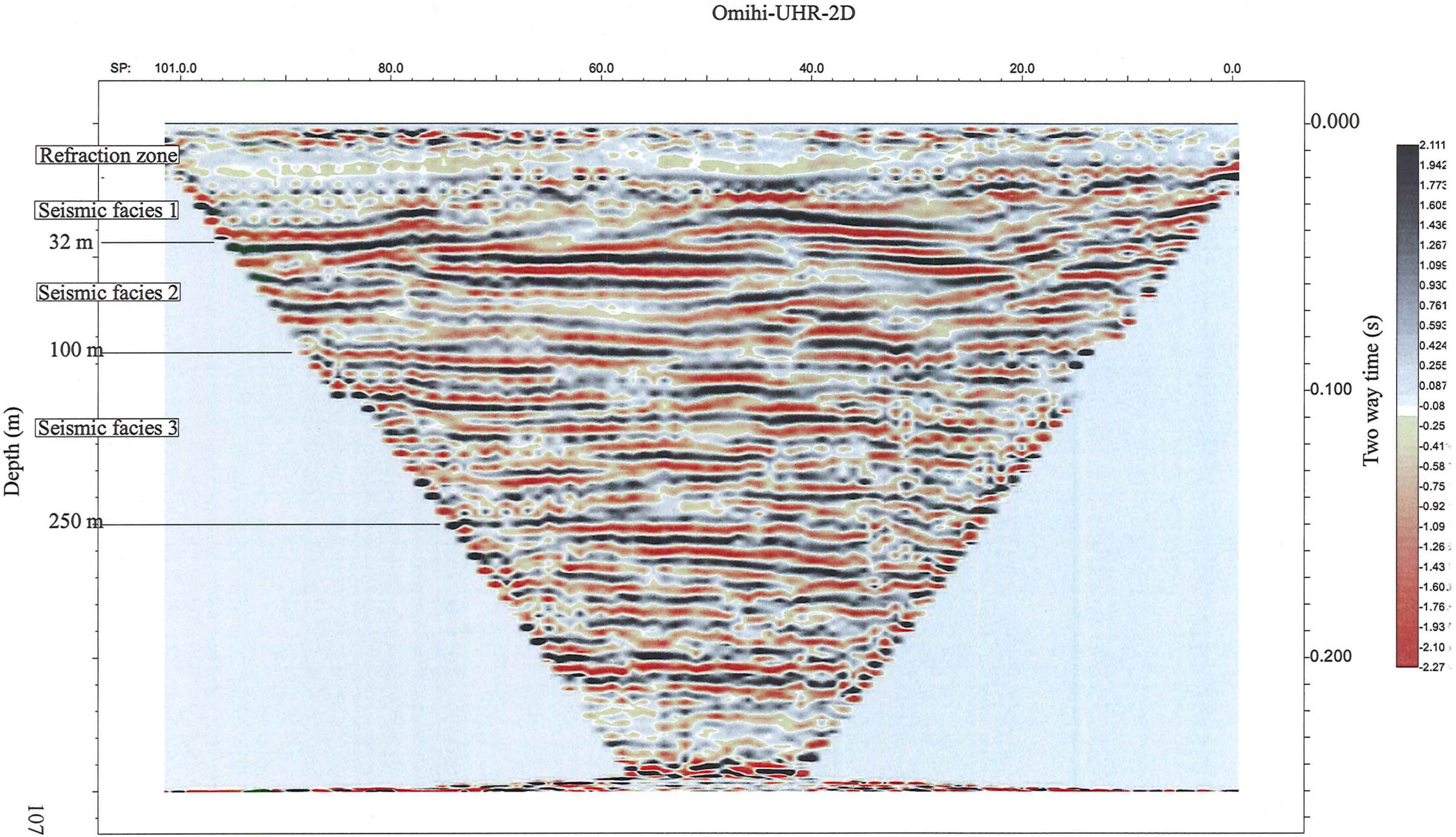


Figure 6.10: Seismic section Omihi-UHR-2D showing main reflection horizons in two way time and depth in metres with the main seismic facies shown. Depth conversion used the velocity model shown in Figure 6.7B.

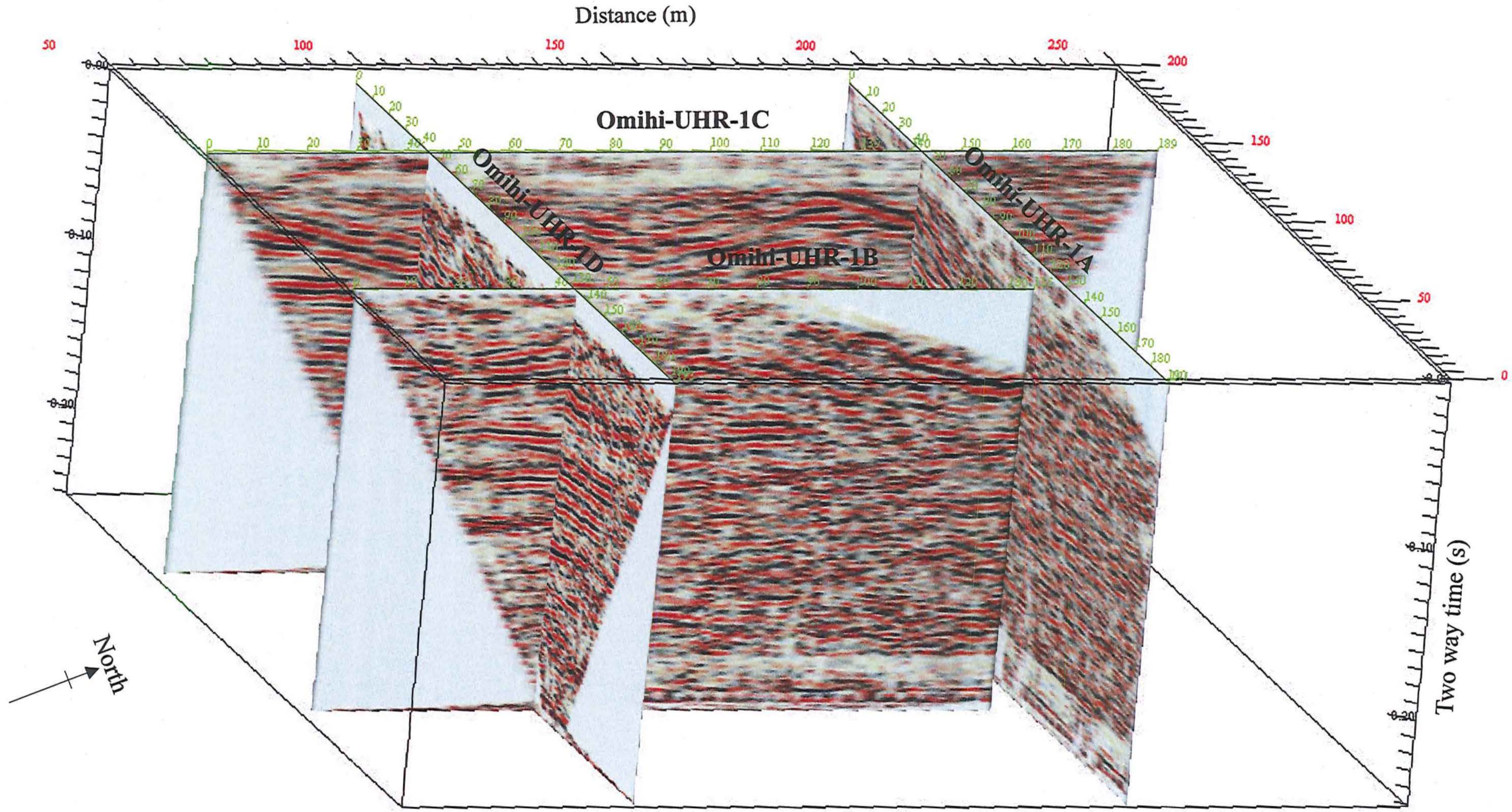


Figure 6.11: Three dimensional representation of the high resolution seismic reflection lines Omihi-UHR-1A through Omihi-1D. Seismic reflection line names are shown in black, shot point positions are marked in green.

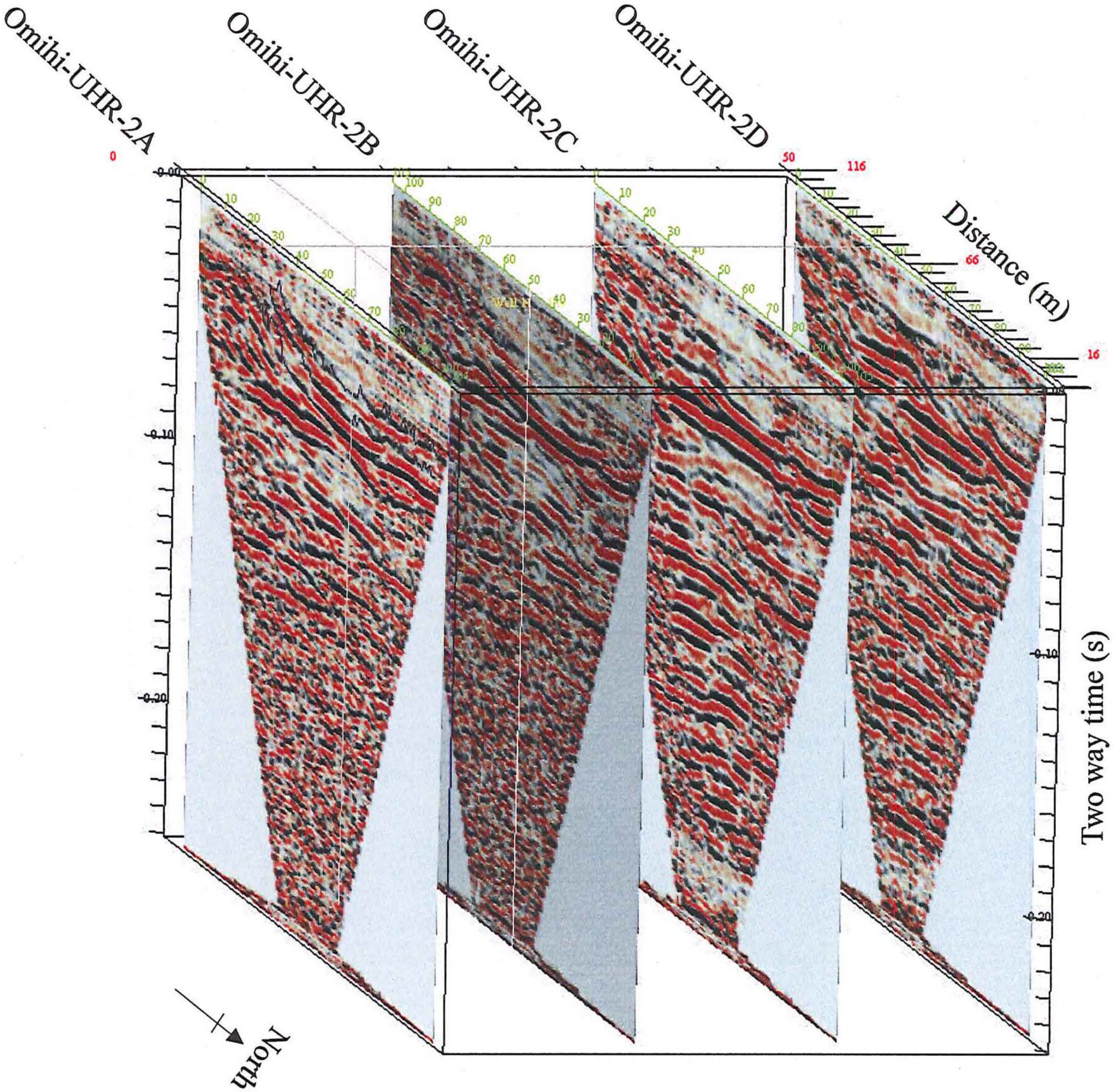


Figure 6.12: Three dimensional representation of the high resolution seismic reflection lines Omihi-UHR-2A through Omihi-UHR-2D. Seismic reflection line names are shown in black, shot point positions are marked in green.

differing units that are encountered. This estimate is based on the visually determined difference between water entering the borehole (foam and water are added as a drilling fluid) and that exiting with the drill cuttings.

The screening of Well N34-139 has several factors effecting its screen depth. During drilling aquifer units were encountered at various depths but the shallower aquifers were unusable because of the conditions set down in the Environment Canterbury consent. The well also penetrated a very good producing horizon at 107 m but this could not be developed, as the sand present would rapidly cause clogging of any screen placed at this depth. The well screen was therefore pulled back to 93 m and the well plugged with bentonite clay to the bottom of this screen (103 m). From Figure 6.4 it can be seen that the hydrology of the well N34-139 can be split into two major divisions. The top 8-60 m section where production is estimated to be in the 5-10 gallons per minute (gpm) range and the lower 90-122 m unit where production is estimated to be in the 10-150 gpm range. Borehole N34-144 has a less well-defined estimated production profile with depth and consists of a unit of low production (0-80 m depth) followed by a more variable unit (80-190 m) with small aquifer units distributed throughout (Figure 6.5).

6.6. Interpretation:

The aim of the two high resolution seismic surveys was two fold; i) to relate seismically defined sedimentary facies and archetecture directly to hydrologic units such as aquifers and aquitards and ii) to use seismic attributes (such as interval velocity) to directly map subsurface hydrological parameters such as porosity, permeability, fluid saturation and silt/clay content.

The only way available to define the subsurface hydrologic units is using the recovered borehole samples. Correlation of the recovered borehole samples with subsurface hydrogeologic units/horizons is not straight forward as the recovered samples are not a set of intact in-situ borehole samples that can be laboratory tested for hydrological parameters (porosity, permeability, grain size etc). The drilling method selected (for economic reasons) results in the collection of highly disturbed and in most cases mixed-horizon samples of the subsurface. The borehole samples therefore represent averaged samples of the subsurface and not distinct depth-lithology samples. The samples are therefore used only to define large-scale (>5 m) hydrological units and facies.

6.6.1. Aquifer/aquitard identification using seismically defined sedimentary architecture:

The initial interpretation of the seismic reflection data involved the correlation of hydrologically facies derived from the borehole samples against the seismically defined facies model.

The interpretation is divided into three stages: I, the division of the seismic profiles into seismic facies with similar seismic characteristics; II, the division of the subsurface using borehole logging and other information such as parameters to establish hydrological units or facies; and III, the qualitative correlation of these two different results to determine if seismic data is capable of deriving useful hydrologic subsurface information.

6.6.2. Stage - 1 Seismic facies:

Borehole N34-144 can be divided into the following seismic facies (Figure 6.9):

Refraction zone (0 – 30 m)

No useable data collected.

Seismic facies 1 (31 - 56 m)

Strong reflector packages near the top, becoming less continuous and of lower amplitude. Some evidence of minor channels or lateral changes in seismic impedance. Reflectors are horizontal to sub-horizontal and appear to lie conformably on the lower reflector package.

Seismic facies 2 (57 - 126 m)

A strong non-continuous reflector is seen at the top of the package, this changes into a set of high and low amplitude reflector units which are laterally discontinuous and sub-horizontal. The individual reflectors show sub-resolution, small-scale, packages, and the unit appears to downlap onto the lower underlying unit.

Seismic facies 3 (127 – 165 m)

Strong horizontal reflectors with what appear to be small features defining the strong reflectors. Seismic facies 3 underlies seismic facies 2 conformably. Inter-reflector spacing ($\approx$ 10 m)

Seismic facies 4 (166 – 180 m)

Strong horizontal reflectors, similar character to the above unit (seismic facies 3) but reflector packages have a smaller vertical spacing ($\approx$ 5 m).

Seismic facies 5 (181 m and below)

Strong reflectors with variable dips. Non-continuous and chaotic in appearance.

Well N34-139

Seismic facies can be divided into the following (Figure 6.10):

Seismic facies 1 (0 – 32 m)

Continuous reflectors with high amplitude, sigmoidal reflectors. The base of the package appears to be an erosional feature with reflectors downlapping onto the reflector.

Seismic facies 2 (33 – 100 m)

Low amplitude, discontinuous reflector packages, sub horizontal, with many features extending >10 m laterally. Many small-scale (< 5 m) truncations. Many units appear to be <4.5 m in thickness.

Seismic facies 3 (101 m and below)

More chaotic reflectors. Some strong amplitude reflectors which are dipping to the south-east. The general character is chaotic.

6.6.3. Stage - 2 Borehole N34-144 and well N34-139 Hydrological units:

Ten hydrological facies are delineated within the Omihi Valley based on recovered well samples. These hydrological facies are shown in Figure 6.13. The hydrological facies are controlled by the relative proportions of the three main sediment types, gravel, sand and silt/clay. The hydrological facies for well N34-139 are shown in Figure 6.4. The well has been sub-divided into eight major hydrological facies with two good producing units, (hydrological facies 1 and 6). Figure 6.5 depicts the sub-division of borehole N34-144 into five major hydrological facies that are inferred to be present in the Omihi Valley. All the hydrological facies are of poor aquifer quality and it is generally only thin (<10 m) clean gravel horizons (hydrological facies 1 and 2) that represent producing layers. The two logs are dominated by clay/slit bound gravel or sand units (hydrological facies 4, 8, 9, 10) for the majority of their depths.

6.6.4. Stage - 3 Seismo-hydrological correlations and relationships:

Correlation of the hydrological facies and seismic facies for well N34-139 and borehole N34-144 resulted in a number of interpretations and key findings, which are covered below.

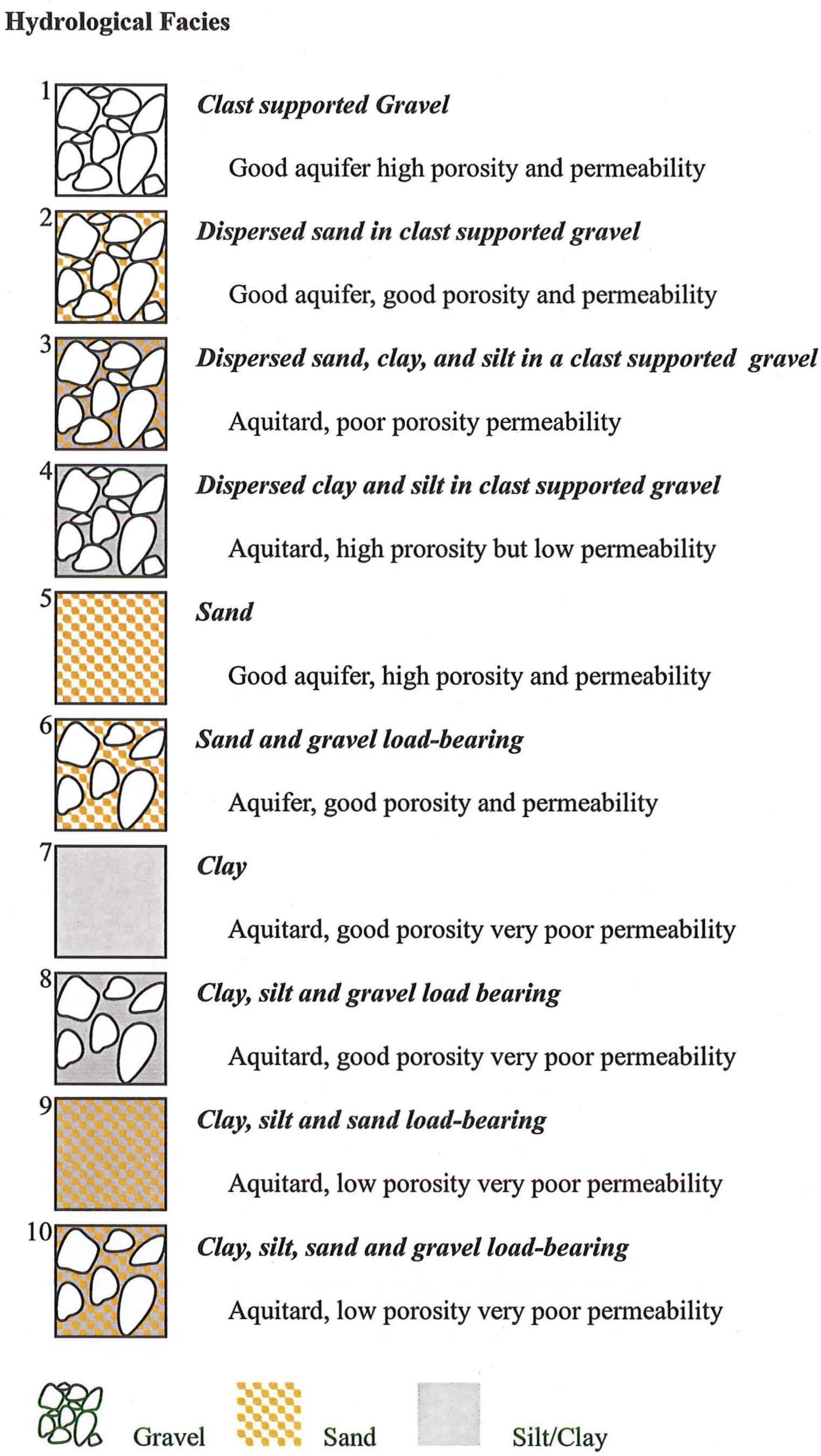


Figure 6.13: Simplified hydrological facies types present in the Omihi Valley.

Well N34-139 has the most complete seismic reflection survey information and several key correlations can be drawn:

1) A strong change in reflector character at 32 m is the result of the change from sandy/clay bound limestone-dominated fine gravels, to Torlesse-derived greywacke clast-dominated fine gravels. The reflector geometry indicates this may be an erosional feature.
2) The low amplitude reflector facies (33-100 m) is the massive clay-bound gravel unit. Well N34-139 does not encounter a major producing unit within this unit and no strong reflectors can be seen within the unit where the well is located. Adjacent to the well location, but not penetrated by the well, several strong reflector packages can be seen which may indicate lateral variations with the unit. As the units are saturated and clay bound any change is likely to represent a change in either the lithology of the clasts (Torlesse to limestone) or a change in the matrix proportions of the clay/silt or sand content. At 100 m a strong reflector is seen at the location of the well. This reflector is interpreted as either the change in medium where the gravels become cleaner or the change from clay matrix medium to sand. The inversion of the seismic wave field indicates a drop in velocity across the interface which correlates with an increase in porosity or clay content.
3) The 100 m and deeper reflector packages are very discontinuous and have a hummocky appearance. They appear to indicate a very different depositional environment, and are correlated with the more sandy and fossiliferous bearing formation below the gravels.

N34-144 has less well defined three-dimensional seismic information but the following correlations can be drawn:

1) The package of reflectors between 31 m and 56 m is interpreted to be hydrological facies 9 and represents mainly silt and clayey sand.
2) The package between 56 m and 106 m is interpreted to be hydrological facies 10 and is represented by increased gravel component.
3) The package between 106 m and 180 m is correlated with hydrological facies 8 and represents a more silty/clayey horizon.

4) The package at 180 m and below, is correlated with hydrological facies 3 and 4 and represents a massive gravel unit.

6.6.5. Interpretation of pseudo- three dimensional seismic surveys:

The surveyed profiles allow three-dimensional interpretation, and the initial step taken included the definition of stratal seismic facies architecture. The three-dimensional profiles were initially interpreted to define architectural detail for the imaged volume. This resulted in a complex seismic stratagraphic model of the subsurface being formed. Many small-scale features that were difficult, or impossible to define on the individual seismic lines became apparent when seen in relation to he adjacent lines. On the array of three-dimensional seismic profiles, many features can be identified, but correlating with neighbouring lines can be improved by using other complex attributes of the seismic wavefield, rather than just simple instantaneous amplitude. The amplitude envelope of the seismic trace shows the average energy over a seismic trace interval without phase effects being incorporated. This allows features that represent a velocity or density change (+/-) to be easily correlated with nearby changes that may be out of phase. Figure 6.14 shows several time slices representing features of interest in the subsurface. As can be seen in this figure many of the features appear to have a general along-valley axis alignment and have a channel-like appearance. These features are interpreted to be small sections of channels or possibily other fluvial features such as channel bars. This interpretation is supported by the following:

1) The majority of the features appear obloid in shape, starting as a small feature at earlier TWT's , growing in width and then reducing again. This is the expected seismic response of flattened tube-like, paleo-channels.
2) The features tend to be aligned along the valley axis, but also show some variability in orientation. This is the expected alignment for paleo-channel features from an early equivalent to the present Omihi stream, which is meandering. With the expected climatic and watershed changes in the Quaternary the paleo-channels would be expected to be meandering, to braided, in form.
3) The features have an average maximum channel width of 10-20 m, which is comparable to the present Omihi stream morphology.

These architectural features indicate that the seismic surveys are capable of delineating the paleo-channel elements, but is not conclusive.

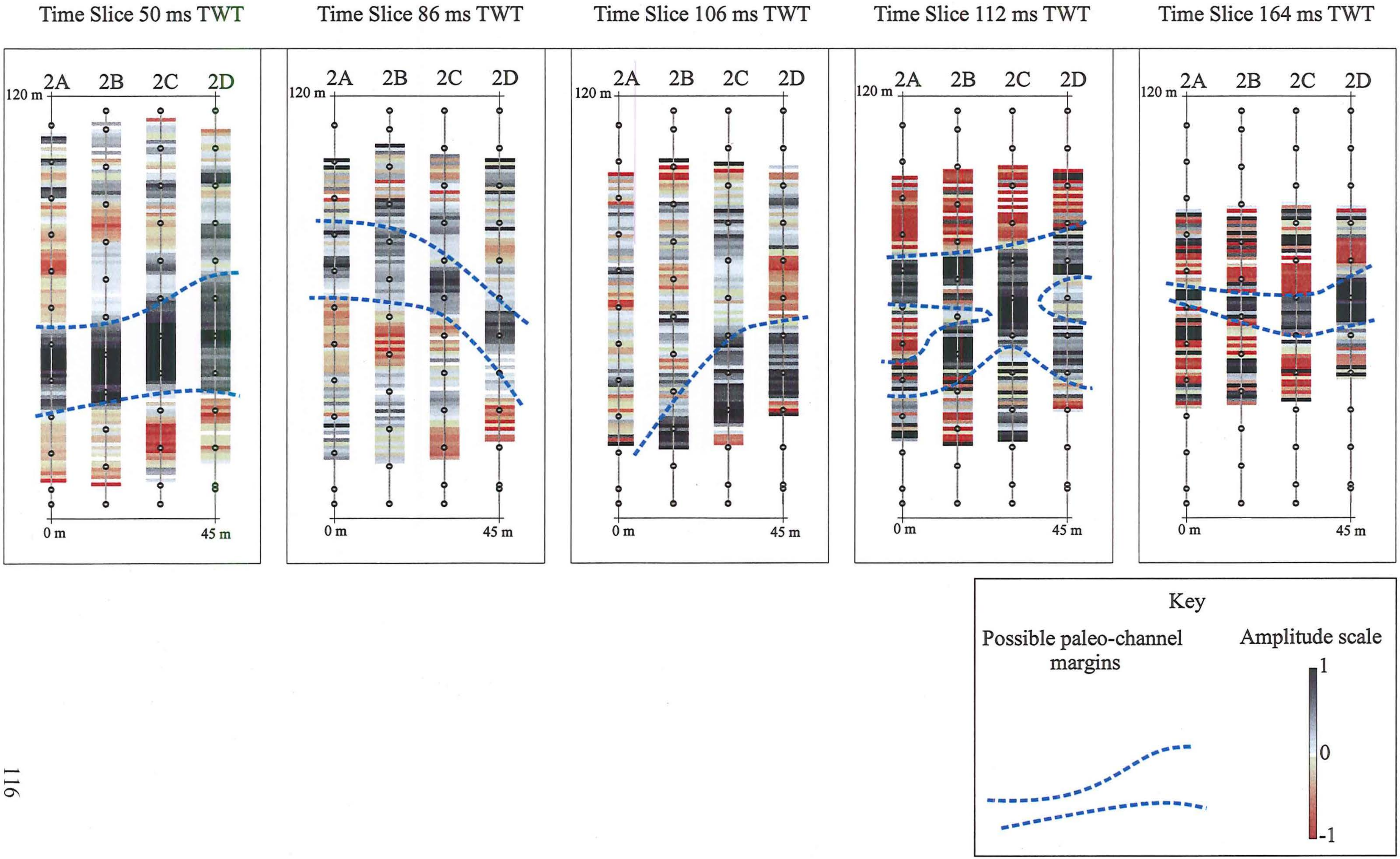


Figure 6.14: Five time slices for seismic reflection survey Omihi-UHR-2A through 2D showing paleo-channel features. Times are two way time.

6.6.6. Mapping subsurface hydrological parameters using seismic interval velocity:

To improve the identification of the features further attribute analysis was attempted on the defined units within the subsurface. Careful velocity analysis of several of the units were undertaken to evaluate if interval velocity changes could be correlated with high permeability gravel lithologies. Initial results indicate that a velocity decrease does occur at approximately 110-145 ms TWT, where cleaner, more productive gravels and sands are encountered in Well N34-139 (96-123 m) (Figure 6.15).

Several other seismic attributes (phase, amplitude envelope), were also analyzed, to evaluate if they could be used to yield further useful information on subsurface hydrological parameters and sedimentary architecture. The attributes selected were based on having been successfully used in hydrocarbon exploration for the discrimination of physical rock properties. Several show possible qualitative correlations between the hydrological facies and seismic character, but without further data no firm correlations can be drawn.

6.7.High resolution synthesis and conclusions:

The high resolution seismic surveys clearly show structural detail within the subsurface, but correlating with individual lithologic units was only possible once a borehole had been drilled and logged adjacent to one of the seismic lines (N34-144). Reflectors appear to be related to grain size, lithology, and saturation, orientation of grains, cementation, and weathering. Therefore seismic does not image saturation unambigously and care must be taken to understand what exactly is being imaged.

Seismic reflection P-wave surveying has the ability to characterise the subsurface for hydrological purposes in several key ways:

1) In the Omihi Valley different hydrological units or sedimentary facies exhibit differing seismic facies. The clay bound gravel unit seen in N34-144 (106 - 155 m) and N34-139 (28 - 96 m) is complex with many small scale reflector packages and dipping events. The amplitude of the reflectors are variable.

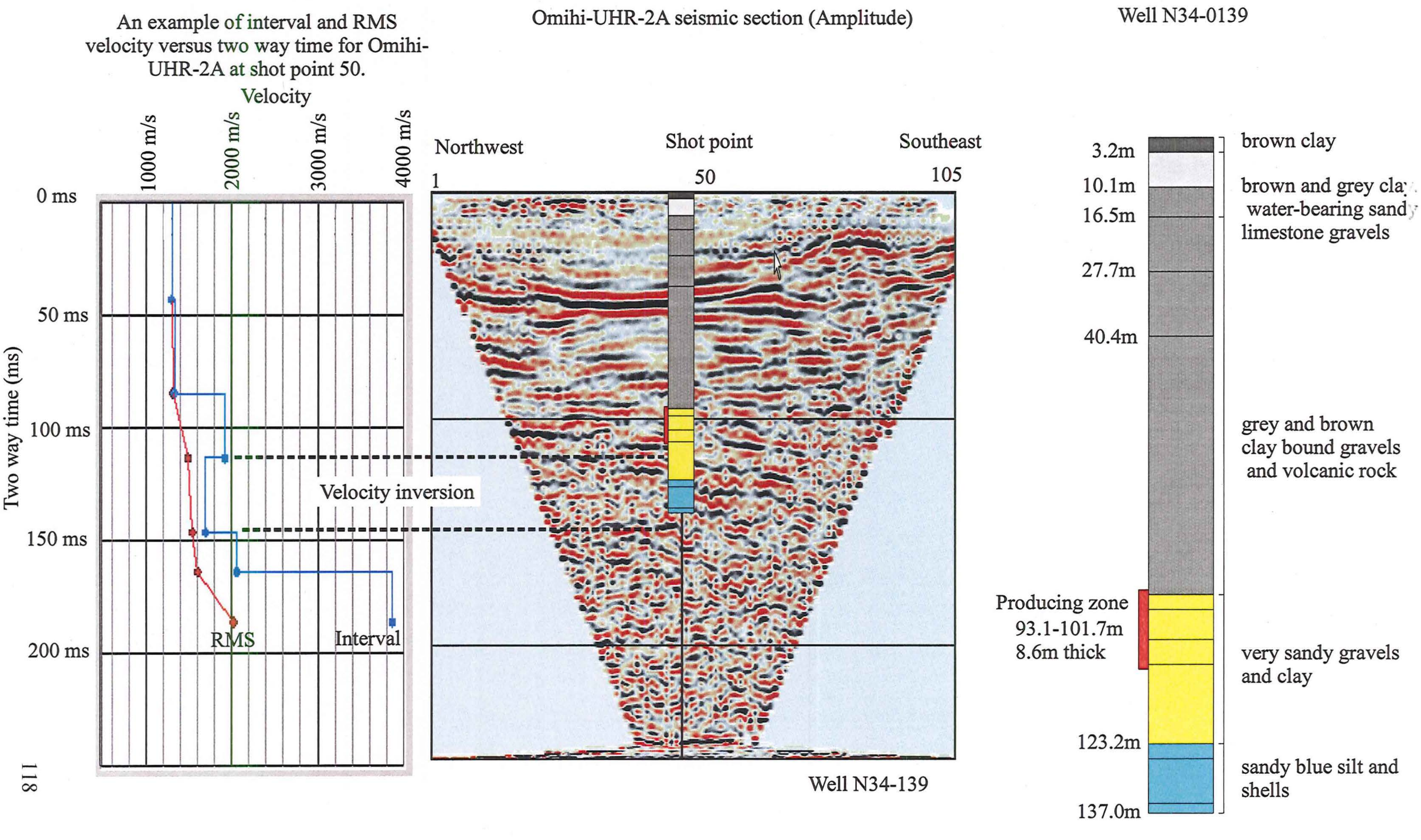


Figure 6.15: An example of possible velocity inversion between 115-140 ms TWT on Omihi-UHR-2A for shot point 50.

2) The deepest reflectors seen below the clay bound gravels are more chaotic. This may indicate that either the units are internally complex and heterogeneous due to there deposition or deformation or that they have few reflectors due to there internal homogeneity and the reflector geometry is an artefact of seismic processing. The preferred interpretation is that the reflector character represents a more heterogeneous unit.

6.7.1. Conclusions:

- Paleo-fluvial sedimentary architecture can be delineated using seismic reflection surveying. The sedimentary architecture is discernible on single seismic lines, but only becomes interpretable once incorporated into a more laterally extensive and detailed pseudo three-dimensional model defined by further surveys.
- The average energy envelope of the seismic traces allows features to be more easily correlated from line to line, especially when time slice analysis is employed.
- A parallel series of two dimensional seismic reflection lines (Figure 6.2) allows complex paleo-channel sedimentary architecture to be more easily identified and mapped than other survey geometries (such as nought and crosses geometry) (Figure 6.1) when imaging the shallow subsurface.
- The seismic pipe gun source has a higher usable bandwidth than the hammer and plate source in alluvial valley fill sediments.
- Seismic lines used for imaging should be several times the length of the expected features to be delineated and the geometry of the source and receivers should be such as to maximise the accuracy of velocity information (e.g. offsets at least as long as the depth of interest).
- The fold should be at least 12 for semblance velocity analysis to be attempted.

Chapter 7. Omihi Valley Conclusions

7.1. Conclusions relating to groundwater resources:

A 200 m deep 8-inch (18 cm) diameter water well costs approximately NZ$50,000 to drill, not including development costs. Any information that reduces the risk involved in "blind" drilling can be very important. Seismic reflection surveys using economically conservative acquisition parameters (NZ$1,000 per km before processing and equipment depreciation) is an economically viable method in reducing the risk for groundwater exploration in geologically poorly defined locations. This thesis has shown that high resolution seismic reflection surveying is good at defining the structurally controlled hydrologic units of the Omihi Valley. Using more detailed higher resolution acquisition parameters seismic reflection surveying is shown to be capable of imaging individual paleo-channel features within the Late Quaternary valley sedimentary fill sequence. These paleo-channels are believed to be the main groundwater aquifers within the valley. The seismic reflection surveys have allowed landowners to reduce the risk of drilling by quantifying the extent of the prospective Quaternary gravel units and to obtain an initial model of the groundwater resources in the valley. The seismic reflection surveys and geologic mapping have identified the most prospective zones for further detailed very high resolution seismic surveying in order to delineate paleo-channels for exploration and development, and have provided the Omihi farming community with information on where further investment in exploration would be most effectively targeted.

The hydrological conclusions pertinent to groundwater exploration and drawn from this study, are summarised in Figure 7.1. Higher yield wells are likely to be contained within the boundary defined by the post-Kowai Formation syncline (Figure 7.1, Zone 1). The western valley margin may contain a considerable (~ 100 m) vertical amalgamation of large-scale paleo-channels that have been incised into the early Quaternary and older Tertiary Formations, because of entrenchment of the Omihi on the western valley margin (Figure 7.1, Zone 3). On the southeastern valley margin, the post-Kowai Formation syncline may be in-filled with margin derived alluvial fan deposits and represent a poor exploration target (Figure

7.1, Zone 2). A similar possibility occurs on the western valley margin where alluvial sediments from the western margin are inferred to have infilled the large-scale, paleo–channels in close proximity to the valley edge. To the north the valley's hydrologic resources appear to be more limited, as Tertiary deposits appear to underlay the surface below a thin (ranging from 0 m - 70 m) Late Quaternary cover sequence (Figure 7.1, Zone 5). The Tertiary age material consists mainly of mudstones and sandstones and is a poor well target because of their very low permeabilities in comparison to Late Quaternary gravels.

Producing aquifers in the valley are of paleo-channel origin and characterised by their limited vertical (< 5 m) and horizon (10 – 30 m) dimensions, and their very complex three dimensional geometries. The top 100 m or so of valley-fill material contains a large amount of silt, clay sediments and fine limestone gravel deposits, and represents the locally derived alluvial fan materials with poor aquifer characteristics. At present, with only one well sample (N34-144) and one outcrop sample the Kowai Gravel is not believed to be a good target for water exploration because it appears to be clay bound. The western margin may contain a large vertical section of paleo-channels that have incised into the Kowai gravels and earlier deposits because the Omihi Stream appears to have been trapped on the western valley side.

7.2. Structural Conclusions:

Structurally the Omihi Valley is a thrust-fault controlled basin, bounded along its eastern margin by the west-directed Omihi thrust fault and associated Black Anticline in the hanging wall. The Omihi Valley is structurally an asymmetric synclinal depression formed in the footwall block of the Omihi Fault. The maximum depth of the Late Quaternary (last 1 million years) deposits (post-Kowai Gravels) infilling the valley-coincident syncline is 200 metres. The fault-controlled synclinal valley and anticlinal ranges bounding the east margin can be subdivided into two structural domains. The southern part of the valley is bound to the east by the thrust-fault propagated South Black Anticline (up-folded strata). The associated Omihi Fault has locally ruptured the ground surface, with several discontinuous active fault traces mapped south of the study area. In the central part of the study area the Omihi Fault is characterised by a step-over, and associated Black Anticline also steps-over to the northwest, and this is reflected by the rangefront re-entrant occurring immediately south of Reece's Road. In the north of the study area the range-forming North Black Anticline and associated Omihi Fault are located immediately east of State Highway 1. The northern part of the Omihi Valley differs markedly from the southern valley insofar as the northern valley is structurally shallowing and narrowing northward, with a maximum Late Quaternary valley fill of approximately 70 metres.

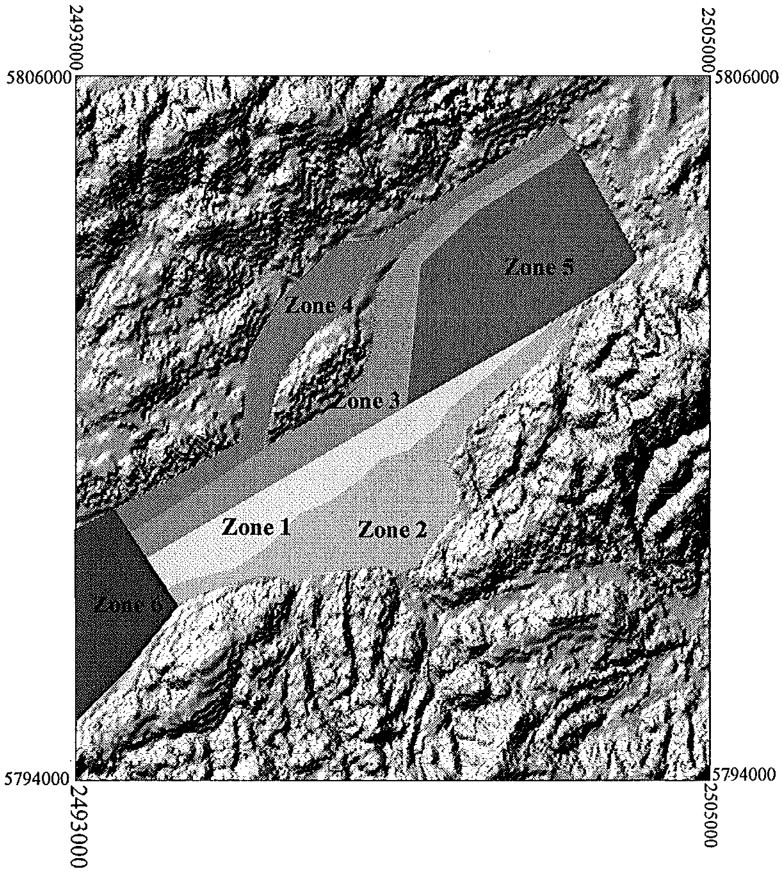
7.3. Overall Recommendations:

Careful reprocessing of the seismic data using advanced processing algorithms (including full topographic correction/migration and depth conversion) may result in a clearer imaging of pre-Kowai deformation. It may also allow clearer images of the structure seen in seismic line Omihi-5 (below the hills) to be delineated and allow any fault system in the north of the valley to be more fully characterised. Reprocessing of the high resolution seismic surveys Omihi-8, Omihi-9, Omihi-UHR-1 and Omihi-UHR-2 with a more carefully derived weathering layer near surface P-wave velocity model may also increase the lateral and vertical resolution of the seismic sections, but the present image is limited by the subsurface attenuation of high frequency energy and is approaching the inherent physical limit. Reprocessing of lines Omihi 4, 5 and 6 with a carefully selected laterally variable velocity model and accurate migration of the reflection data may allow the tectonic/stratagraphic architecture of the Mt Brown and older lithologies to be delineated. Many of the geometric patterns seen in the Mt Brown Formation may be resolvable once detailed processing and migration are undertaken. The northern part of the valley therefore offers a location were the mid to small scale sedimentary structure of the Mt Brown Formation can be clearly imaged with high resolution seismic and where topography is minor. If the sand/siltstone/mudstone and gravel units within the Mt Brown formation can be characterised it may be possible to target a gravel unit within the Mt Brown Formation marine sands for groundwater extraction. If saturated, as they are believed to be, this would identify a new aquifer resource in this area of North Canterbury.

Much work has been undertaken on the sedimentary evolution of extensional basins due to their importance on hydrocarbons/mineral deposits and preservation of sedimentary climate and fossil records (Gawthorpe et al., 2000). Much less work has been undertaken on thrust controlled basins. The Omihi Valley seismic reflection data, detailed geologic and initial geomorphic mapping offer an opportunity to examine the sedimentary response of a thrust controlled valley to ongoing active tectonic regime and in particular the structural architecture defined within the structural depression and co-eval accumulation sediments.

The Omihi Valley near the Omihi Township, offers a good location to build on the work of previous researchers in characterising the Late Quaternary tectonic history of this area of North Canterbury e.g. (Campbell and Nicol, 1992; Nicol et al., 1994; Pettinga and Armstrong, 1998). This characterisation is dependent on obtaining age control from the horizons seen in the seismic lines Omihi-1 and Omihi-3. With this information it should be possible to quantify (for one fault system) the rate of deformation throughout the Late Quaternary.

The focus of this study is to develop an understanding of the tectonically controlled aquifer architecture of the Omihi Valley and to assist with groundwater resource assessment and allocation. This study has not attempted to provide a detailed structural analysis with respect to the tectonic setting, but has generated seismic reflection data which could be used for that purpose in the future.



Zone 1
Within the post Kowai Gravel syncline, but away from valley margins and associated alluvial fans.

Zone 2
Within the post Kowai Gravel syncline, but near to valley margin alluvial fans.

Zone 3
Paleo-channel incision into the underlying Kowai and pre-Kowai deposits.

Zone 4
Paleo-channel incision into the underlying Kowai and pre-Kowai deposits but alluvial fan material intermittently present.

Zone 5
Probable Tertiary strata to the near surface, with possible paleo-channels in several areas. Poorly understood at present.

Zone 6
Not investigated in this study, but likely to be a continuation of zonation 1-4 at edge.

Figure 7.1: Zonation of groundwater resources in the Omihi Valley, northwest Canterbury, draped over a topographic model of the valley. New Zealand Map grid NZ260.

Part III

Part III

North Canterbury Plains Seismic Reflection Surveys

Outline of Part III:

Part III describes the research undertaken at three field areas on the North Canterbury Plains (Figure 8.1a). These three field areas are chosen to evaluate the effectiveness of the shallow seismic reflection method in various north Canterbury Quaternary sedimentary and active tectonic environments.

Four main seismic reflection lines (for other survey lines undertaken, but not included in this thesis, refer (Finnemore and Pettinga, 2000) have been completed in the northwest Canterbury Plains adjacent to Racecourse Hill and Burnt Hill. These surveys are designed to characterise the shallow (< 500 m deep) Tertiary and Quaternary geology, and quantify what, if any sedimentary architecture could be delineated in the glacio-fluvial sandy-gravel dominated sediments (Figure 8.1b).

Burnt Hill and Racecourse Hill (surveys 1 and 2) are located close to the point of emergence from the eastern foothills of the late Quaternary glacial outwash fan that constitute the northwest Waimakariri river composite aggradation surface (Brown et al., 1988). The area is interpreted to be dissected by repeated episodes of river incision forming paleo-valleys and aggradational infilling, where aggradation during glacial periods is followed by incision and degradation during the intervening interglacial periods (Von Haast, 1864; Doyne, 1865; Von Haast, 1879; Gage, 1958; Brown et al., 1988; Bal, 1996).

The third small survey was undertaken at Pines Beach on the northeast coast of the Canterbury Plains (Figure 8.1a). It is designed to quantify the use of shallow seismic reflection methods in a more extensively reworked prograding postglacial gravel braidplain environment where repeated episodes of marine incursion have generated a composite stack of permeable (gravel/sand) and less permeable (mud and silt) units over the last 700 kyr (Brown, 1998).

Part III is divided into five chapters. Chapter 8 gives a general introduction to the Burnt Hill, Racecourse Hill and Pines Beach areas, including their geography and geology. Chapter 9 describes the methodology of the seismic reflection surveys undertaken in each of the field areas. Chapter 10 details the results obtained from these surveys. Chapters 11 and 12 present a synthesis of the results with conclusions and recommendations pertaining to the northwest Canterbury plains.

Chapter 8. Introduction

The aim of this chapter is to define the geographic location of the three field areas, and to describe the geology of those three field areas based on the work of previous researchers.

8.1. Geographic setting:

The three surveys are located in two distinct geographic areas. The Burnt Hill and Racecourse Hill surveys are in the Northwest Canterbury Plains, adjacent to the eastern foothills of the Southern Alps, while the Pines Beach survey area is located on the northeast coast adjacent to Pegasus Bay, and immediately north of the Waimakariri River mouth (Figure 8.1a).

Burnt Hill is a volcanic inlier that rises above the surrounding Canterbury Plains. It forms a prominent feature with an east-facing dip-slope formed on mid Tertiary basalt flows, and a west-facing escarpment (McLennan, 1981). Burnt Hill is located 5 km southeast of the Waimakariri Gorge and 1 km north of the present degradational Waimakariri River bed. To the southeast of Burnt Hill and the Waimakariri River is the small inlier of Racecourse Hill. The topographic expression includes two low hills, and these are depicted in Figures 8.1b, 8.2 and 8.3.

Pines Beach is located on the northeastern Canterbury coast, 20 km north of Christchurch, and adjacent to Pegasus Bay. The beach is a gently sloping sand beach, with a shallow drop off into Pegasus Bay (average depth of 20 m). The Waimakariri River mouth is located 1 km south of the location of the survey (Figure 8.4 and 8.5).

8.2. Geology of Burnt Hill:

8.2.1. Introduction:

Burnt Hill is a 2 km^2 inlier rising 100 m above the surrounding Canterbury Plains. The hill is capped by basalt flows, which dips 10° east-southeast. Underlying the basalt a Tertiary sedimentary sequence which drilling confirms to be at least 278 m deep (McLennan, 1981). Dating of the basalt (Harper Hill basalt) at Burnt Hill by McLennan using stratigraphic considerations gives a late Miocene or earliest Pliocene age. Browns Rock, a small rock

Figure 8.1a: The location of Pines Beach, Racecourse Hill and Burnt Hill field areas in relation to the Northern Canterbury Plains. Figure 8.1b: A more detailed location map of seismic lines in on the Northwestern Canterbury Plains adjacent to Racecourse Hill and Burnt Hill inliers. The red dotted lines show the location of the seismic reflection lines.

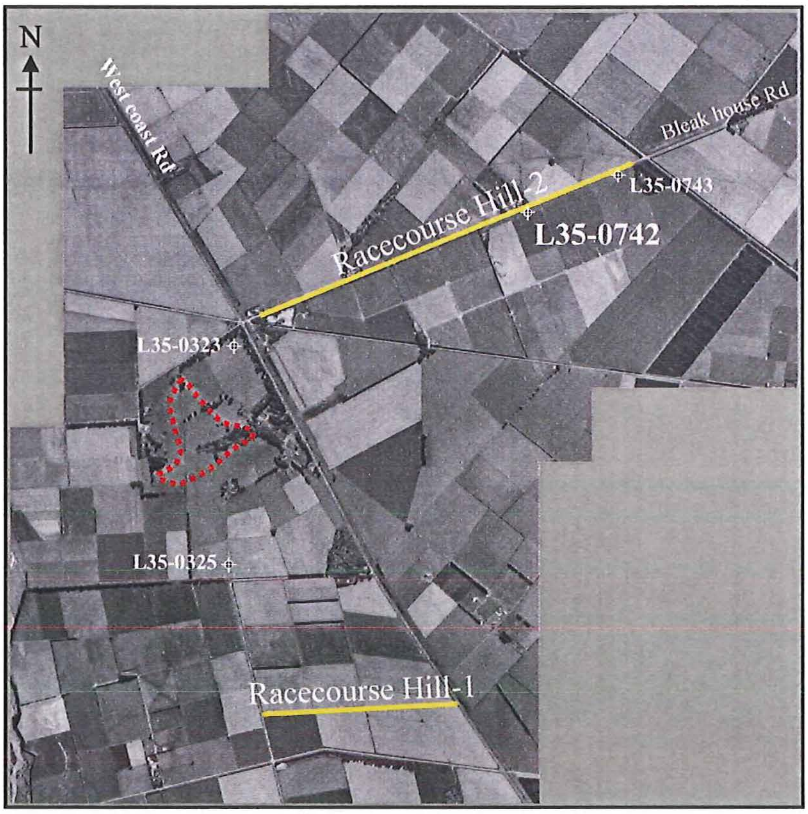


Figure 8.2 Aerial photograph the Racecourse Hill inlier showing the location of the seismic reflection lines Racecourse Hill-1 and Racecourse Hill-2 and the main geomorphic features are shown.

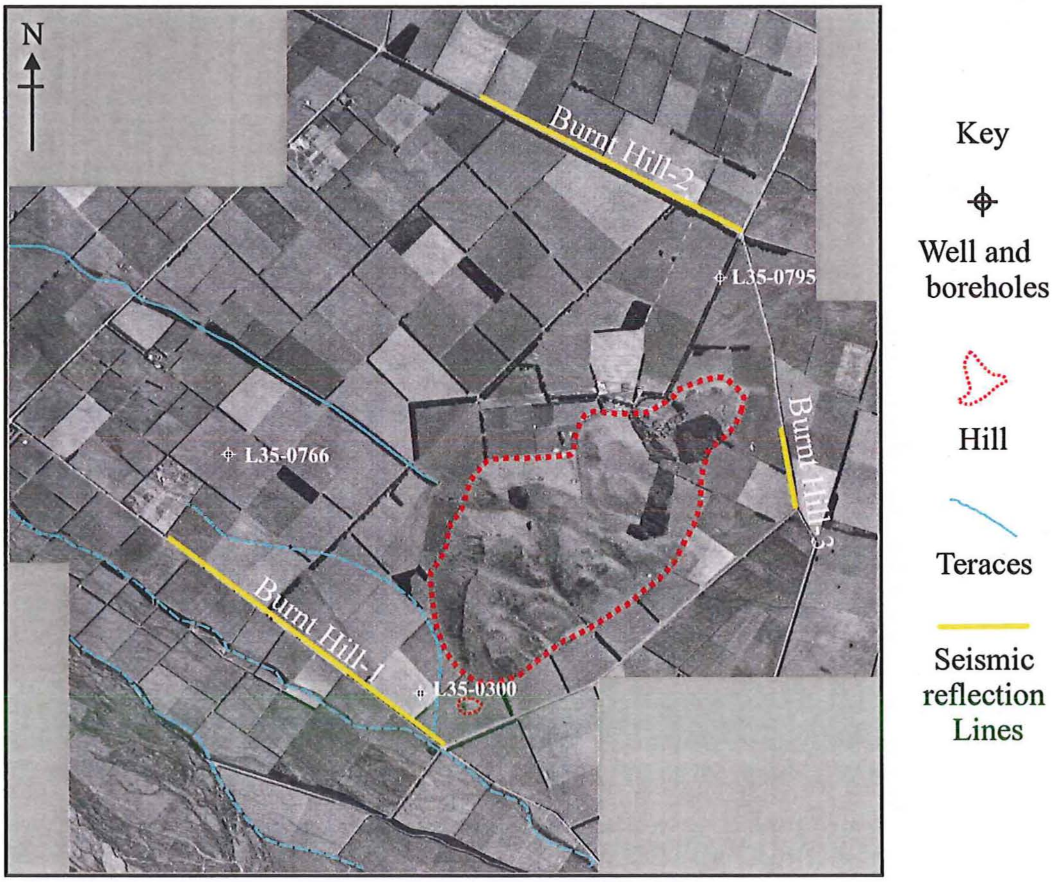


Figure 8.3: Aerial photograph the Burnt Hill inlier showing the location of the seismic reflection lines Burnt Hill-1, Burnt Hill-2 and Burnt Hill-3 plus the main geomorphic features.

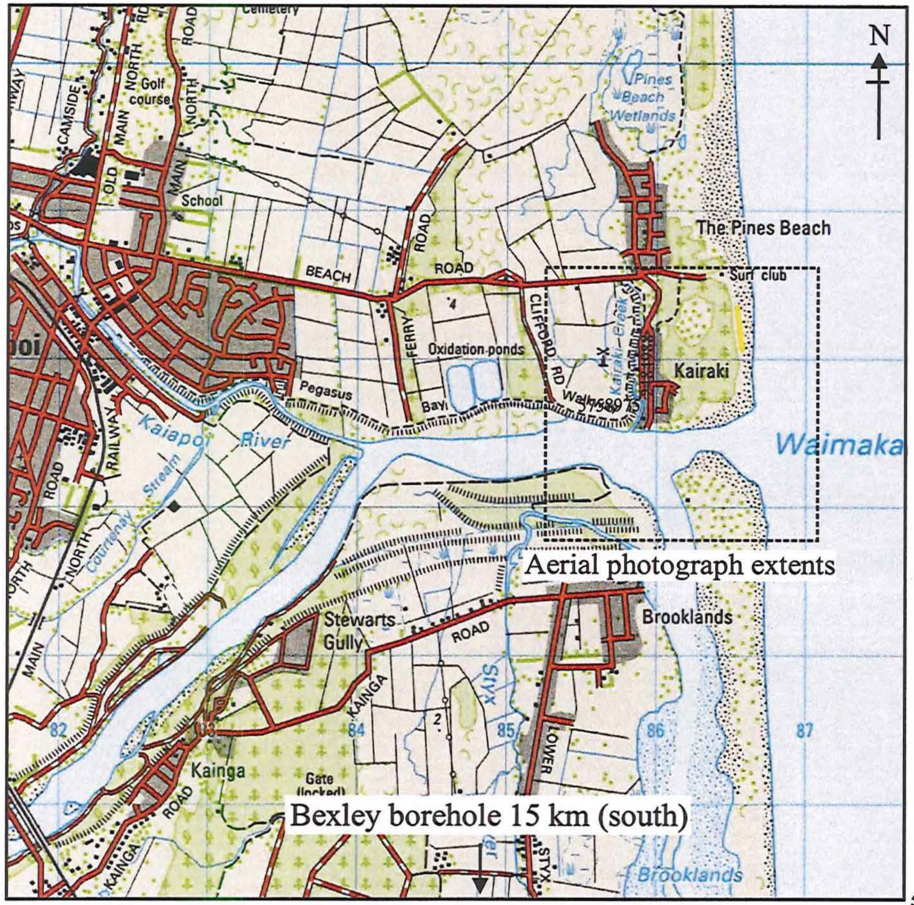


Figure 8.4: Location of the Pines Beach seismic reflection survey. Original map supplied by Land information New Zealand NZMS 260 topographical maps.

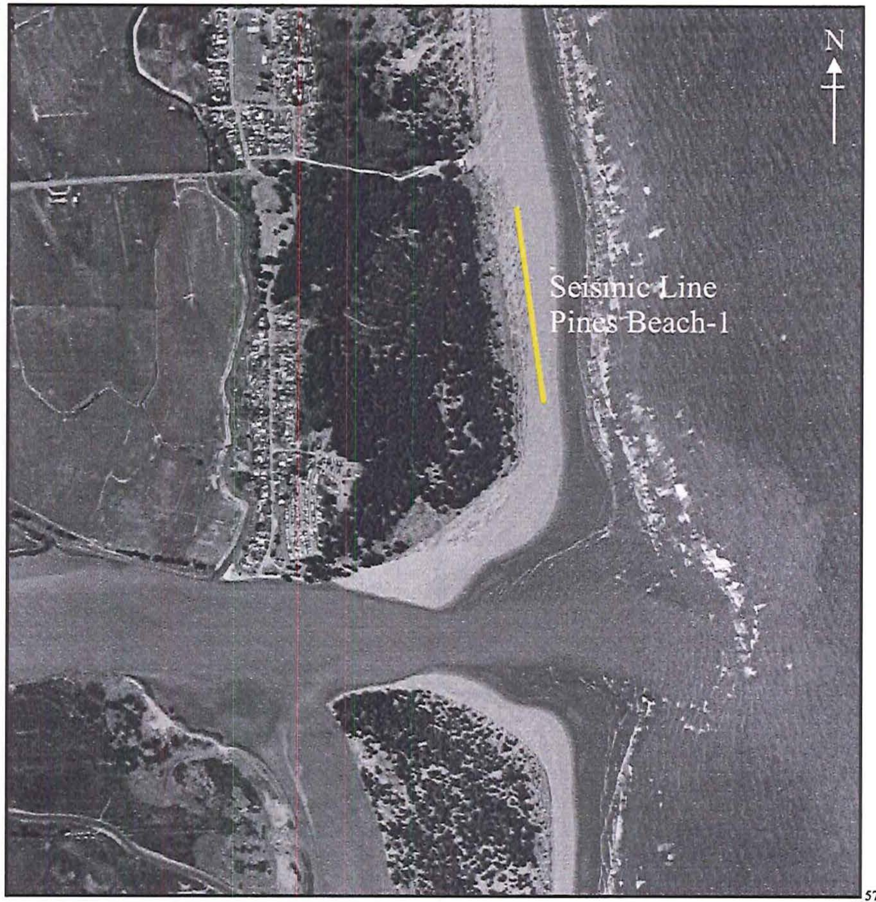


Figure 8.5: Aerial photograph showing the location of the Pines Beach seismic reflection survey. Digital photograph supplied by Terralink International Ltd.

promontory located 3.5 km to the west on the banks of the Waimakariri River, has a similar chemical composition to the volcanics (Harper Hill basalt) at Burnt Hill and this indicates that the two sites are stratigraphically related (McLennan, 1981). Recent attempts to date the volcanics at Browns Rock using Ar-Ar and K-AR have proved impossible due to the degraded/weathered nature of the material per. comm. V. Tappenden.

Water wells drilled in the vicinity Burnt Hill have encountered gravels (assumed to be Torlesse clasts, but these materials were not described in detail in well logs) to depths of 200 m except for two wells drilled on the northern flank of Burnt Hill, where sandstone was penetrated at 29 m (Well L35-0008) and at -46 m (L35-0250) (ECan, 2004).

8.2.2. Stratigraphy:

The stratigraphy of the Burnt Hill and Avoca region is defined by Carlson et al. (1980) and McLennan (1981). The stratigraphic nomenclature of Field and Browne (1989) is used. From oldest to youngest:

***Torlesse Supergroup** (Mesozoic)*

Basement in northeast Canterbury consists of well indurated grey sandstones and mudstones of the Mesozoic Torlesse Supergroup. Structurally the Torlesse Supergroup is characterised by intense faulting and deformation with the presence of wide crushed zones.

***Broken River Coal Measures** (Eocene)*

Quartzose Sandstones which are white to light grey, poorly indurated, non-calcareous, massive and finely bedded, very fine to medium quartzose sandstone, jarositic laminated mudstone and sub-bituminous rank coals.

***Iron Creek Formation** (Eocene)*

Glauconitic sediments which include Eocene basalt lava flows.

***Whitestream Formation?** (Oligocene or younger age)*

The deepest formation seen in borehole L35-0300 is the Homebush sandstone, but at Oxford, Homebush Sandstone overlies conformably the White Stream Formation and it is assumed that a similar situation occurs at Burnt Hill (Carlson et al., 1980).

***Homebush Sandstone –Burnt Hill Group** (Oligocene or younger age)*

The Homebush Sandstone is described by McLennan as "a pale greenish to yellowish grey, unconsolidated, burrowed, moderately sorted, slightly muddy, fine sand: uncemented, slightly glauconitic feldsarenite, but with slight lithological variations". The relationship of the Homebush Sandstone to the underlying beds is unknown as the borehole L35-0300 did not penetrate below the Homebush Sandstone. To the north of Oxford township the Homebush Sandstone is believed to overlie the White Stream Formation with what is believed to be a conformable contact. The thickness of the unit in outcrop at Burnt Hill is at least 60 m and a further 220 m were penetrated in the borehole, giving a total of 280 m. The Homebush Sandstone has not been directly dated at Burnt Hill, but at Oxford to the north it is of Dannevirke to Arnold age (35 to 46 myr). At Burnt Hill the formation underlies the Thongcaster Formation which has been dated to the Oligocene or younger age.

***Thongcaster Formation – Burnt Hill** Group (Late Oligocene or younger age)*

This formation was defined by Carlson et al. (1980) as a "massive brown fine sandstone highly glauconitic, including a 0.6 m thick basal greensand, markedly clay rich ... with well-leached mollusca and shark teeth". The Thongcaster Formation overlies the Homebush Sandstone with a disconformity and an intensely burrowed horizon. The Thongcaster Formation is 3.7 m thick at Burnt Hill but only 1.55 m thick in the unit recovered from the borehole. The formation from paleotological evidence is not older than the Landon Series (24 – 35 myr) so only a Late Oligocene or younger age can be assumed.

***Wairiri Volcaniclastite –Burnt Hill Group** (Late Oligocene to early Miocene)*

This formation was defined by Carlson et al as a "massive breccia, tuff-breccia and alternating sandy and silty tuffs". A more detailed description of the formation by McLennan was " consisting of medium *brown to grey, hard, decimetre-bedded, poorly sorted, muddy medium to fine sandstone; carbonate-cemented quartzose volcaniclatite, with centremeter-decimeter-thick mudstone or ash beds present". The formation conformably overlies the Thongcaster Formation with a sharp contact. The formation is 3.5 m thick in outcrop and in the borehole at Burnt Hill. Foraminifera from the immediate overlying unit are of Altonian-Lillburnian age (13 -19 myr) giving an inferred age of Late Oligocene to early Miocene.*

Taragar Sand *(Early Miocene to middle Miocene)*
This Formation was proposed by McLennan (1981) and comprises "a pale yellowish grey, consolidated, massive, moderately well sorted, muddy very fine sand; uncemented subfeldsarenite ". The Taragur Sand overlies the Wairiri Volcaniclastite and has a moderately sharp contact. Burrows are seen in the Taragur Sand but do not extend into the underlying Wairiri Volcaniclastite, indicating that consolidation or lithification had occurred prior to deposition of the overlying Taragur Sands. The Taragur Sands are over 25 m thick in outcrop at Burnt Hill and 25.5 m in the nearby borehole. The basal tuffaceous unit and shelly quartz beds have been dated Altonian-Lillburnian (13 - 19 myr) and Waiauan (11 - 13 myr) from foraminifera.

Sandpit Tuff – Burnt Hill Group – Type Locality Sand Pit Coalgate *(Middle Miocene)*
The Sandpit Tuff was defined by Carlson as "alternating beds of brown and red, coarse and fine, sandy and silty tuffs and tuff breccias with leaf impressions and leached stems". The contact between the tuff and the underlying Taragar Sand is poorly exposed but appears to be sharp. The formation is 2 m thick at Burnt Hill but only cuttings were recovered from the borehole as the thickness of the unit is unknown. The flora does not indicate an age, but on stratigraphic grounds a Taranaki Series age is likely as it overlies the Altonian to Waiauan age Taragur Sands, and the Nearby Harper Hills lies below the Coalgate Bentonite (late Miocene).

Bluff Basalt *(Middle Miocene)*
Carlson et al. (1980) describes this unit as: "The basalt is fragmented in places with rectangular joint pattern it is dark grey generally but pale pink where oxidised. It is a non-vesicular porphyritic basalt". The formation overlies the Sandpit Tuff and is stratigraphically below the Harper Hills Basalt. The formation consists of labradoritic basalt and at Burnt Hill is seen as a lava flow. The Bluff Basalt is only 0.6 m thick at Burnt Hill.

Harper Hill Basalt *(Middle Miocene 10.5 +/- 0.3 myr)*
Described by Carlson et al. (1980) as "a dark grey, vesicular porphyritic olivine basalt commonly exhibiting pipe vesicles". At Burnt Hill, at least three flows are identified. It is believed that the nearby Browns Rock is a dike, sill or possibly a flow of Harper Hill basalt and therefore the Harper Hill Basalt is more extensive than seen in outcrop at Burnt Hill.

8.2.2.1. Quaternary Stratigraphy

The Quaternary stratigraphy for the Burnt Hill and Racecourse Hill areas is shown in Figure 8.6, and is based on the work of Wilson (1989).

Kowai Formation*(1.1 – 1.5 myr)*
This Nukumaruan/Opoitian Formation is found extensively throughout the Canterbury region. It is a brown, weathered, silty gravel and fine sand.

Hororata Formation*(250 – 310 kyr)*
Brown, friable, high-level gravel; surface slightly dissected; loess cover up to 15 m thick. The formation is Waimaungan/Nemonan in age.

Woodlands Formation*(120 - 150 kyr)*
Morainic deposits; fluvioglacial outwash gravel composed of brown, silty, poorly sorted gravel; loess cover averages 1.5-2 m thick. Waimean in age.

Bromley Formation*(70 -150 kyr)*
Peat and silt of Kaihinuan age. Not seen in the Northwest Plains area.

Windwhistle Formation*(40 -70 kyr)*
Fluvioglacial outwash gravel composed of cream-brown pebbles with sand and silt matrix; gravel typically poorly sorted; capped by loess averaging 1 m thick.

Burnham Formation*(14 – 27 kyr)*
Fluvioglacial outwash gravel composed almost entirely of greywacke pebbles with creamy matrix of sand and silt; gravel typically coarse and poorly sorted; capped by loess averaging 0.7 m.

Springston Formation*(0 - 14 kyr)*
This formation consists of several members and spans the Holocene. The individual members in general represent fluvial gravel, sand, silt that has been deposited as the result of reworking and degradation of older gravels.

Quaternary Geology of Northwestern Canterbury Plains

Geological Legend based on Miscellaneous Series Map 14 1:100,000 Quaternary Geology of Northwestern Canterbury Plains, Department of Scientific and Industrial Research, 1989.

SERIES	STAGE	Unit	Description	MEMBER	FORMATION	GROUP
QUATERNARY – HOLOCENE	ARANUIAN	fa*, faw	Silt, sand, and gravel cf present day river channels.			
		sp, sp*, spw	Fluvial gravel, sand, and silt, largely from degradation of older gravels, and gravel of former river channels; peat, silt, and sand accumulated in swamps (now drained).		Springston (sp)	
		spyw	Fluvial gravel, sand, and silt, largely from degradation of older gravels; gravel of former river channels and alluvial silt.	Yaldhurst (spy)	Springston (sp)	
		sphw	Fluvial gravel, sand, and silt, largely from degradation of older gravels.	Halkett (sph)	Springston (sp)	
		spcw	Fluvial gravel, sand, and silt, largely from degradation of older gravels.	Courtenay (spc)	Springston (sp)	
		sprw	Fluvial gravel, sand, and silt, largely from degradation of older gravels.	Riverview (spr)	Springston (sp)	
		spbw	Fluvial gravel, sand, and silt, largely from degradation of older gravels.	Bleak House (spb)	Springston (sp)	
QUATERNARY – PLEISTOCENE	OTIRAN	bu*	Fluvioglacial outwash gravel composed almost entirely of greywacke pebbles with creamy matrix of sand and silt; gravel typically coarse and poorly sorted; capped by loess averaging 0.7 m thick.		Burnham (bu)	
	OTIRAN	le*	Fluvioglacial outwash gravel composed of cream-brown pebbles with sand and silt matrix; gravel typically poorly sorted; capped by loess averaging 1 m thick.		Windwhistle (le)	
	KAIHINUAN	ro	Peat and silt.		Bromley (ro)	
	WAIMEAN	wo*	Morainic deposits; fluvioglacial outwash gravel composed of brown, silty, poorly sorted gravel; loess cover averages 1.5-2 m thick.		Woodlands (wo)	
	WAIMAUNGAN NEMONAN	ho	Brown, friable, high-level gravel; surface slightly dissected; loess cover up to 15 m thick.		Hororata (ho)	
	NUKUMARUAN OPOITIAN	ko	Brown, weathered, silty gravel and fine sand.		Kowai (ko)	
TERTIARY – PLIOCENE, MIOCENE		b	Interbedded volcanogenic sediments and basalt flows.			Burnt Hill (b)
TERTIARY – OLIGOCENE		ox	Cream, moderately hard coccolith-foraminiferal chalk.		Oxford Chalk (ox)	
TERTIARY – EOCENE, PALEOCENE		e, ev	Undifferentiated sediments, predominantly soft sandstone with subordinate conglomerate, coal measures, and siltstone (e); basaltic pillow lava, flows, and sills (ev).		View Hill Volcanics (ev)	Eyre (e)
CRETACEOUS		m	Calc-alkaline volcanics consisting of rhyolite flows, domes, tuff, and ignimbrite; subordinate andesite and dacite.			Mt Somers Volcanics (m)
CRETACEOUS / JURASSIC		wa	Conglomerate, carbonaceous mudstone, and muddy fine sandstone; abundant plant fossils.		Wakaepa (wa)	
TRIASSIC	REGIONAL UNCONFORMITY	t, tv	Well indurated dark grey greywacke and argillite (t); interbedded basic volcanics (tv).			Torlesse Supergroup (t, tv)

- a Ashley River
- c Cust River
- e Eyre River
- h Hawkins/Waianiwaniwa
- k Kowai River
- o Hororata River
- r Rakaia River
- s Selwyn River
- w Waimakariri River

GEOLOGICAL SYMBOLS

Contact
- Located accurately
- Located approximately
- Terrace forming contact

Fault
- Located accurately
- Located approximately
- Late Quaternary fault trace

Bedding (strike and dip) — Not overturned / Overturned
- Face defined at outcrop — 45 / 70
- Face inferred from field relationships — 15
- Face unknown — 55

Minor lithologies
- Peat
- Alluvial silt
- Sand
- Gravel of former river channel
- Moraine

TOPOGRAPHICAL REFERENCE

- Railway (with station)
- National or Provincial State Highway
- Other road
- Built-up area
- Trig station — 56
- Terrace
- River
- Stream
- Contour, vertical interval 100 metres — 300
- Intermediate contour, vertical interval 50 metres — 250

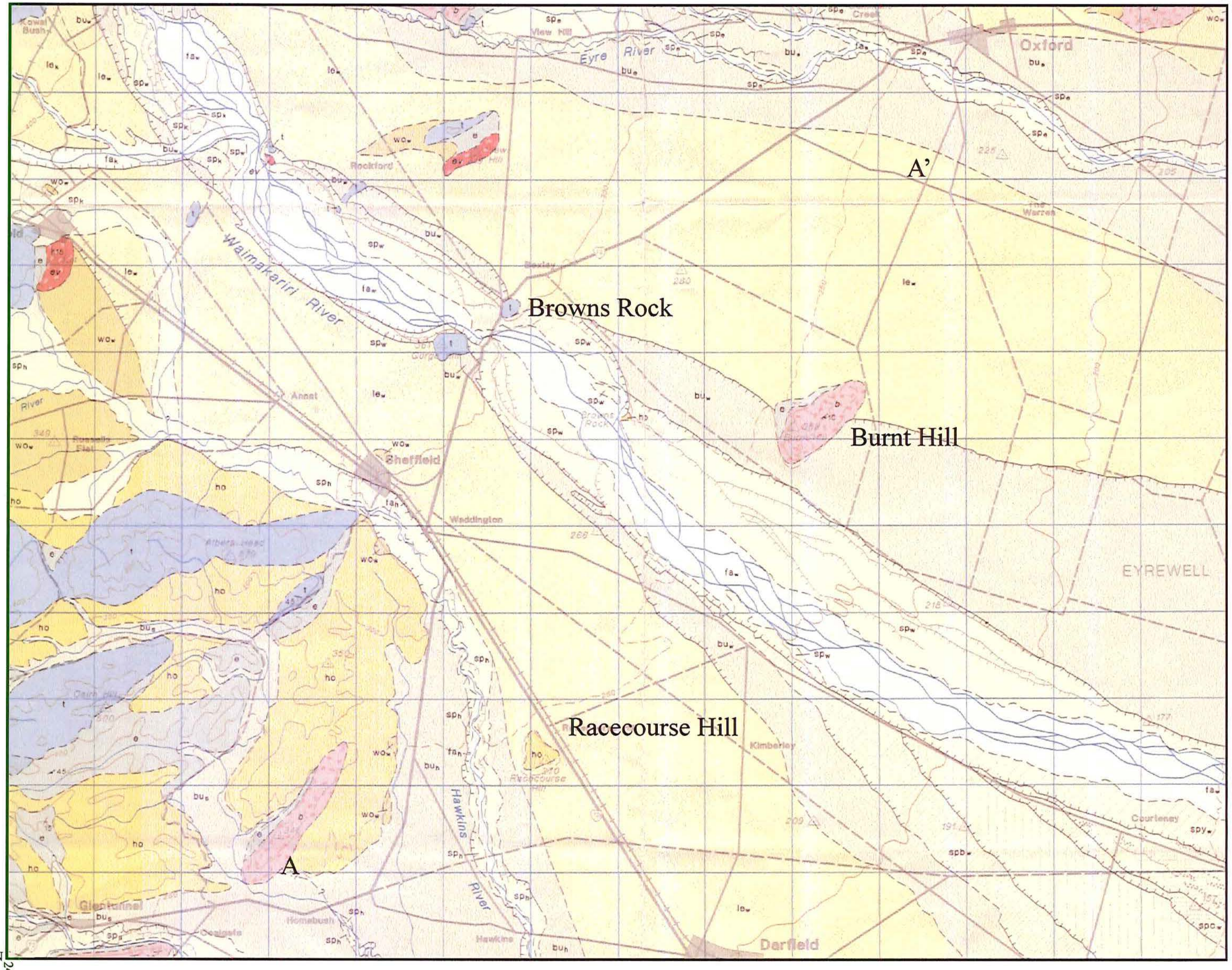


Figure 8.6: Quaternary Geology of Northwestern Canterbury Plains, based on Miscellaneous Series Map 14 1:100,000 Quaternary Geology of Northwestern Canterbury Plains, Department of Scientific and Industrial Research, 1989.

8.3. Geology of Racecourse Hill:

The geology of Racecourse Hill is poorly known, with only Quaternary age sediments seen in outcrop and only regional scale geophysical subsurface surveys undertaken in this area before this thesis (Reilly, 1970; Reilly et al., 1979; Hicks, 1989). Racecourse Hill is mantled by Hororata Formation glacio-fluvial sediments (Waimaungan/Nemonian age, 250 – 310 kyr) (Brown et al., 1988). These sediments are older than the surrounding Windwhistle Formation glacio-fluvial outwash surface (Otiran age, 40 – 70 kyr) and these in turn are covered in thick loess cover (Brown et al., 1988; Wilson, 1989). The height of the present surface, and its location, indicates that the Racecourse Hill inlier is associated with similar aged glacio-fluvial remnants located around the northeastern Plains margins, and therefore may represent an erosional remnant of an earlier more extensive glacial outwash surface (Wilson, 1989). This is supported by the very flat, horizontal top surface of the Hill and the large boulders seen on this surface. No boreholes or wells have penetrated the top surface and no ages are available, so ages and lithology for Racecourse Hill are assigned using visual correlation with known outcrops located elsewhere on the Canterbury Plains. From the known stratigraphic succession elsewhere beneath the Canterbury Plains (Brown et al., 1988), it is believed that the Hororata Formation deposits are underlain by Kowai Formation (1.1 - 1.5 myr) and that below these are a series of Mesozoic to Tertiary-age formations similar to those identified throughout the Canterbury region (Carlson et al., 1980; McLennan, 1981).

Structurally Racecourse Hill appears to represent a discontinuity in the subsurface. A water well (L35-0325) from 250 m south of Racecourse Hill, has penetrated to 255 m through clay bound non-producing Torlesse derived gravels. While 100 m due north of Racecourse Hill, glauconitic sands (inferred to be Lower Tertiary age) have been identified at a depth of 11 m in a water well (L35-0323). It is therefore assumed that Racecourse Hill represents an erosional remnant that has both tectonic and erosional control rather than a simple erosional remnant. Geomorphic setting and interpretations support this conclusion (J.R. Pettinga pers comm., 2004).

8.3.1. Basin margin aquifers:

Aquifer/aquitard formation on the western Canterbury Plains closer to the foothills of the Southern Alps, and within the range-front glacial outwash fans, differs from the coastal model. The aquitards consist of the outwash gravels which have only minor working and sorting. These sediments contain a high percentage of fines and have low permeability (Aiken et al., 1994; Fetter, 2001). The aquifers are the fluvially reworked gravels deposited during interglacial/postglacial incision or possibly during the initial stages of glacial aggradation when sediment volumes are small. For the aquifers to be retained the incision must have reached its deepest point or channel migration must have caused further incision to have moved to another area. With the onset of a glacial environment the incised valleys are infilled with low permeability outwash sediment and the cycle repeated during the next interglacial event.

At some point the sediment supply, tectonic and isostatic uplift reach equilibrium and incision ceases. The rivers then attempts to maintain their stream profiles, as is believed to be occurring today (Browne and Naish, 2003), and they avulse forming wide braidplains.

8.4. Geology of Pines Beach:

The geology of the Pines Beach area is based on deep seismic reflection surveys undertaken by BP Ltd (1960) (Kirkaldy and Thomas, 1963) and the New Zealand Oceanographic Institute N.Z.O.I. (1989) and surface mapping of the Quaternary sediments undertaken by Brown (1973) and geophysical and hydrogeology research by Field (1999), Lovell (1998), Barnes (1995), Barnes (1993).

The BP Ltd oil exploration seismic line runs along the coast and parallel to it, from the Waipara area, south to Christchurch (BP seismic Line 5N and 5S) Appendix 8 - Map 1 (Kirkaldy and Thomas, 1963). The NZOI seismic line is shallow marine line located 6 km offshore and sub-parallel to the coast Line number Cr.2034-16 NZOI, (Barnes, 1993). The BP Ltd line shows that below the northeastern Canterbury Plains adjacent to the coast, a series of broad synclinal and anticlinal structures occur in the subsurface, which have Late Quaternary sediments onlapping them (Jongens et al., 1999). This deformation is believed to be related to the northeast-southwest trending Pegasus Bay Fault System (Barnes, 1993; Pettinga et al., 1995). It appears from the seismic reflection data and the Bexley test borehole located 10 km to the south adjacent to the coastline (Brown, 1998), that the Late Quaternary sediments which consist of a composite stack of permeable (gravel/sand) and less permeable (mud and silt) units are variable in thickness, ranging from 200 - 400 m. These sediments appear to be uncomformably onlapping the Early Quaternary Kowai Formation which appears deformed and up to 400 m thick. The BP Ltd seismic line shows little detail within the Late Quaternary sediments, while the NZOI (Cr.2034-16) line shows more detail but is more representative of the basin-ward marine Late Quaternary environment which lies to the east and offshore.

The Bexley borehole (433 m deep) located 15 km due south of Pines Beach is an area that represents a similar sedimentary environment during the Late Quaternary (Brown, 1998). This borehole shows a series of interfingering gravel, sand, clay, peat and shell bed units to a depth of over 428m, representing a sequence of glacio-eustatic sea-level controlled fluctuations. These sequences have been tentatively dated using palynological samples and assigned Oxygen isotope ages 1,6,9,11,13 (14 ky, 200 kyr, 350 kyr, 400 kyr, 500 kyr) (Brown, 1998). It is assumed that the Pines Beach shallow (0 - 400 m) Quaternary sediments represent a similar shifting fluvial-marine transition. No wells are drilled to greater than 61 m (60.8m - M35-6662) within 1 km of the Pines Beach survey, which makes correlation with known stratigraphy difficult.

8.4.1. Coastal aquifers:

The aquifers below the eastern Canterbury Plains (adjacent to the location of the present coast) consist of fluvially reworked alluvial fan/braidplain sediments. During postglacial incision secondary permeable fans and braidplains formed on the Canterbury Plains which either: 1) flooded the existing interglacial estuarine environment with course grained permeable gravels forming aquifer units, or 2) deposited reworked gravels before interglacial and postglacial eustatic sea level rises occurred. These aquifers were then covered by later postglacial estuarine, marine and lagoonal deposits that accumulate as the postglacial sealevel rise inundates the inner shelf regions existing coast plains during glacial sealevel lowstands. Due to subsidence of the Plains during the Quaternary in the southern Pegasus Bay area (Brown and Weeber, 1992) a repetitive sequence of inter-fingering fluvial gravel/sand sediments (aquifer units) and marine estuarine clay/mud (aquitard units) have been deposited.

8.5. Burnt Hill and Racecourse Hill Structure:

Burnt Hill and Racecourse Hill are reviewed here together because of their close geographic proximity and the assumption that the underlying active tectonic controls are similar for both areas.

8.5.1. Structural setting:

The North Canterbury Plains are believed to be underlain by a northeast-southwest trending step in the Mesozoic-Cenozoic basement rocks running from Rangiora Township to Ashburton Forks (Appendix-8 Map 1) (Atkins and Hicks, 1979)(Jongens et al., 1999). Basement depth on the Northwest side of this step is determined from seismic reflection data (Indo Pacific Ltd Line 2 and BP Ltd Line 2, Appendix-8 Map 1) to be ~300 m (Jongens et al., 1999). To the south of this step it is estimated from gravity data to be ~1300 m (Atkins and Hicks, 1979). The step in basement is associated by Jongens et al. (1999) with the Hororata and Springbank Faults, and it has been suggested that the step may represent a Quaternary age, southeast facing reverse or thrust fault. It is believed that the Racecourse Hill and Burnt Hill structures are related to this fault and may represent backthrusts of the Hororata-Springbank fault system.

The backthrust model is supported by the structural pattern of the Hororata fault where the Southeast facing main fault has a series of Northwest back thrusts bringing basement rock to the surface.

In the northern section of the Canterbury Plains a similar but less evolved structural pattern is observed for the Springbank Fault (Estrada, 2003) (Jongens et al., 1999) where the Cust Anticline is identified as fault propagated fold associated with the main back thrust of the Springbank Fault.

Faulting in the North section of the Canterbury Plains appears to be more complex than in the southern section of the Canterbury Plains at Hororata as the Cust anticline swings in trend to the east. Similar swings in trend are observed by Yousif (1988) and Barnes (1993) in north Canterbury and offshore north Canterbury. "Given the horizontal compression direction of North Canterbury is northwest-southeast (Nicol and Wise, 1992) it has been suggested that the widespread easterly swings in structural trends are the result of interaction between reactivated east-west Cretaceous basement faults and the direction of principal horizontal compression. Thus, a dextral strike-slip component, especially on the east-west segments of faults, is implied." (Jongens et al., 1999)

8.5.2. Structure:

The outcropping geology in the Burnt Hill and Racecourse Hill areas has been only generally mapped and only limted age control is available (Carlson et al., 1980; McLennan, 1981; Wilson, 1989). Burnt Hill forms an asymmetric cuesta of presumed Cretaceous sequences with basalt flows forming a resistant capping and strike ridge dipping 15° to the SE. Unfortunately, further outcrop of pre-Quaternary stratigraphy is sparse in the area and any structural model is therefore limited, requiring further subsurface information. No seismic reflection surveys have been undertaken in this area before this thesis with the exception of a single seismic refraction survey at Springfield, located 16 km northwest of Burnt Hill (Woodward and Hicks, 1987). This survey gives only limited information on the basement topography. The only other geophysical method applied in the area is gravity surveying (Hicks, 1989). The gravity survey resulted in the Burnt Hill and Racecourse Hill areas being surveyed at 1 station per 4 square kilometres (McLennan, 1981). The resulting isostatic anomaly map is presented in Figure 8.7. A unique interpretation of the gravity anomaly map is not possible due to the non-unique nature of the inversion of the gravity data, but there is a general northeast-southwest trend in the isostatic gravity data which parallels the rangefront topography to the north and south of the Waimakariri River Valley re-entrant. This isostatic gravity anomaly can be interpreted in several ways:

- An increasing bulk density of the subsurface, resulting from a change in lithology laterally (northeast-southwest); or
- A decreasing depth to basement, where basement is the transition from less consolidated Quaternary/Tertiary sediments to more indurated/and or metamorphosed older, more dense units such as indurated Torlesse Supergroup sandstones and argillites (Garrick and Hatherton, 1973).

It is thought to be unlikely that lateral changes in lithology generate the gravity anomaly, as the Tertiary units in the Burnt Hill area are characterised by sandstones, mudstones, and tuffs (McLennan, 1981). These have similar low-medium densities and so would be unlikely to generate the anomaly seen, and they are also known from surface mapping to be regionally extensive suggesting limited lateral stratigraphic variation occurs. The isostatic gravity anomaly is more likely to be the result of basement (Torlesse Supergroup) or another similar dense, thick lithologic unit shallowing (ramping) toward the Southern Alps foothills to the northwest.

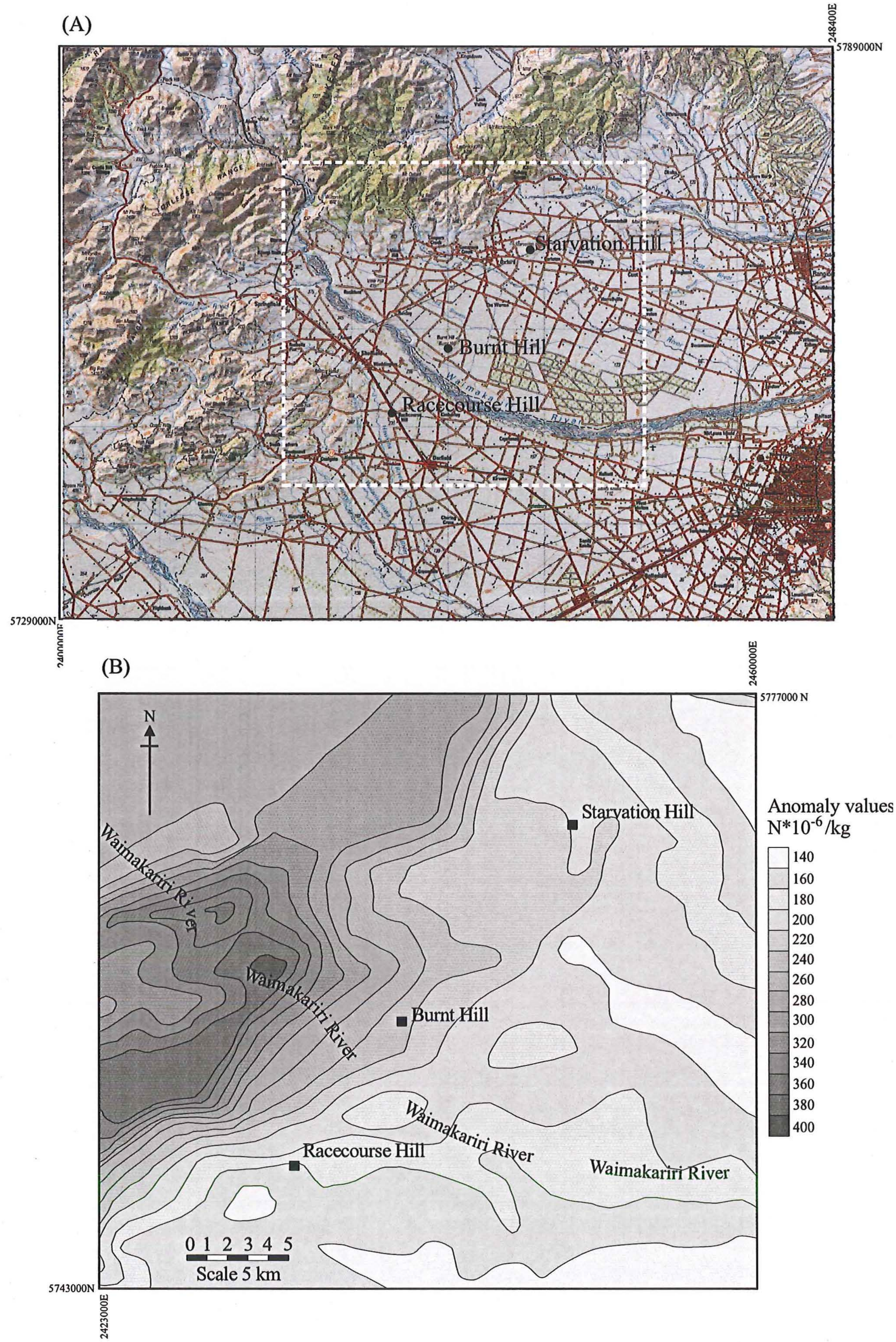


Figure 8.7: (A) Topographic map of the Northwestern Canterbury Plains showing the area of gravity isostatic anomaly map (white dotted square). (B) Gravity isostatic anomaly map of the Burnt Hill and Racecourse Hill areas (Modified from McLennan 1980).

Chapter 9. Methodology

This chapter describes the seismic reflection surveys undertaken in the three field areas (Racecourse Hill; Burnt Hill; Pines Beach) and also the associated topographic mapping, borehole logging and limited geomorphic analysis.

9.1. Racecourse Hill seismic reflection surveys:

After initial seismic reflection walkaway testing indicated that seismic reflection surveying would be successful in the Racecourse Hill area, two seismic lines were undertaken: Racecourse Hill-1 and Racecourse Hill-2. The surveys, funded by a local landowner, were initially designed to assist with water well placement in the area. The first seismic profile Racecourse Hill-1 (1.1 km in length) is located to the south of Racecourse Hill and runs across several grazing paddocks parallel to Homebush Road (Figure 8.2). The seismic source used was a 10 kg hammer and plate. This seismic line was also repeated using a mini-Sosie© source in an attempt to improve the imaging quality, but this proved unsuccessful and no further processing of the mini-Sosie© data was undertaken. The second seismic line, Racecourse Hill-2 (2.4 km in length) is located along the Bleak House Road, starting from the junction with State Highway 73 (Figure 8.2). The acquisition parameters for the two seismic lines are shown in Table 9.1 and Table 9.2

Table 9.1 Acquisition Parameters for Racecourse Hill-1	
Source type	Hammer and plate 8-16 impacts
Source point minimum offset	0 m
Source point maximum offset	282 m
Shot interval	12 m
Shot points	92
Geophone type	3 series geophones, grouped, inline, 30 Hz Mark Products
Geophone group interval	6 m
Shooting spread	48 Channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000 Hz) 1 second

Table 9.2 Acquisition Parameters for Racecourse Hill-2	
Source type	Hammer and plate 8-16 impacts
Source point minimum offset	0 m
Source point maximum offset	282 m
Shot interval	12 m
Shot points	200
Geophone type	3 series geophones, grouped, inline, 30 Hz Mark Products
Geophone group interval	6 m
Shooting spread	48 Channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000 Hz) 1 second

9.2. Burnt Hill seismic reflection surveys:

Two seismic reflection survey lines and several smaller test survey lines (Finnemore and Pettinga, 2000) were undertaken at Burnt Hill. The two main lines, Burnt Hill-1 and Burnt Hill-2, are located several hundred metres to the north and south respectively of Burnt Hill and perpendicular to the inferred strike of the local geology (Cowan, 1992; Jongens et al., 1999). Seismic line Burnt Hill-1 is located along Thongcaster Road, starting at the junction of Dog Trail Road and running northwest (1.2 km) (Figure 8.3 and Appendix 8 - Map 3). Seismic line Burnt Hill-2 ran northwest along Parish Road starting at the junction of Parish Road and Burnt Hill Road (1.2 km) (Figure 8.3 and Appendix 8 - Map 3). Several smaller test lines are also located to the north and east of Burnt Hill. These smaller test lines were designed to image near surface intra-gravel reflectors. This survey work is described in a report to Environment Canterbury (Finnemore and Pettinga, 2000), but is not further detailed here. The acquisition parameters for the lines Burnt Hill-1 and Burnt Hill-2 can be found in Table 9.3 and Table 9.4.

Table 9.3 Acquisition Parameters for Burnt Hill-1	
Source type	Hammer and plate 8-16 impacts
Source point minimum offset	0 m
Source point maximum offset	260 m
Shot interval	10 m
Shot points	120
Geophone type	3 series geophones, grouped, inline, 30 Hz Mark Products
Geophone group interval	5 m
Shooting spread	48 Channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000 Hz) 1 second

Table 9.4 Acquisition Parameters for Burnt Hill-2	
Source type	Hammer and plate 8-16 impacts
Source point minimum offset	0 m
Source point maximum offset	260 m
Shot points	120
Shot interval	10
Geophone type	3 series geophones, grouped, inline, 30 Hz Mark Products
Geophone group interval	5 m
Shooting spread	48 Channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000 Hz) 1 second

9.3.Pines Beach seismic reflection survey:

The Pines Beach seismic reflection survey was undertaken on 10 May 2003. It consisted of a single 300 m seismic line using a towed geophone array (Appendix 7 for details) and a single seismic reflection walk-away shot gather test using standard seismic CDP cables and geophone strings (Appendix 7).

All surveying was undertaken at low tide on a clear and calm day (< 10 knots of wind). The 24 element towed array was pulled along Pines Beach in a north-south direction by a four wheel drive vehicle and stopped every 4 m where a shot was undertaken. A simple hammer and plate seismic source was used with the steel plate resting on the sand surface. In total 58 shot points were completed. Acquisition parameters for the towed array survey are shown in Table 9.5.

Several comparison shots were also undertaken using the standard seismic reflection walk-away setup at the centre of the towed array seismic line. The acquisition parameters for walk-away test are shown in Table 9.6.

Table 9.5 Acquisition Parameters for Pines Beach, Towed Array	
Source type	Hammer and plate 4 impacts
Source point minimum offset	0 m
Source point maximum offset	46 m
Shot points	58
Geophone type	40 Hz Mark Products vertical
Shot interval	4 m
Geophone group interval	2 m
Shooting spread	24 channel towed array
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000 Hz) 1 second

Table 9.6 Acquisition Parameters for Pines Beach walk-away test	
Source type	Hammer and plate 8 impacts
Source point minimum offset	1 m
Source point maximum offset	48 m
Shot points	1
Geophone type	3 series geophones, grouped, inline, 30 Hz Mark Products
Geophone group interval	2 m
Shooting spread	48 Channels centre spread
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000 Hz) 1 second

The water table is located 30 cm below the sand surface, obtained from a small hole dug along the seismic line. No effort was made to repeat this measurement during the course of the seismic surveys as all data was collected within 1 hour of the measurement of the water table depth. The sand was damp and cohesive in the vadose zone and saturated below the water table.

9.4. Racecourse topographic surveys:

Topographic surveying was undertaken in October 2001 along the roads surrounding Racecourse Hill. A series of vehicle-mounted GPS transacts were undertaken using a Trimble ProXR rover and corrected using P-code base data collected in Christchurch (60 kms from the field area). The post-processed GPS rover positions have an accuracy of +/- 0.5 m in the horizontal and 1 m in the vertical. The sampling interval was 5 seconds and the surveying vehicle had a maximum speed of 15 km/hour. This gives lateral distance travelled during each sample point of ≈ 21 m. The survey therefore represents the average of the height and position over this distance. Small scale features less than twice this sampling interval (42 m) are therefore unlikely to be spatially sampled with enough sample points to be correctly defined using Nyquist sampling theory (Nyquist, 1928). This data was then gridded using the Kriging gridding method and a topographic model defined using Davis (2002) around Racecourse Hill. The data points were then draped over the defined model to allow the survey point locations to be identified (Figure 9.1 and 9.2).

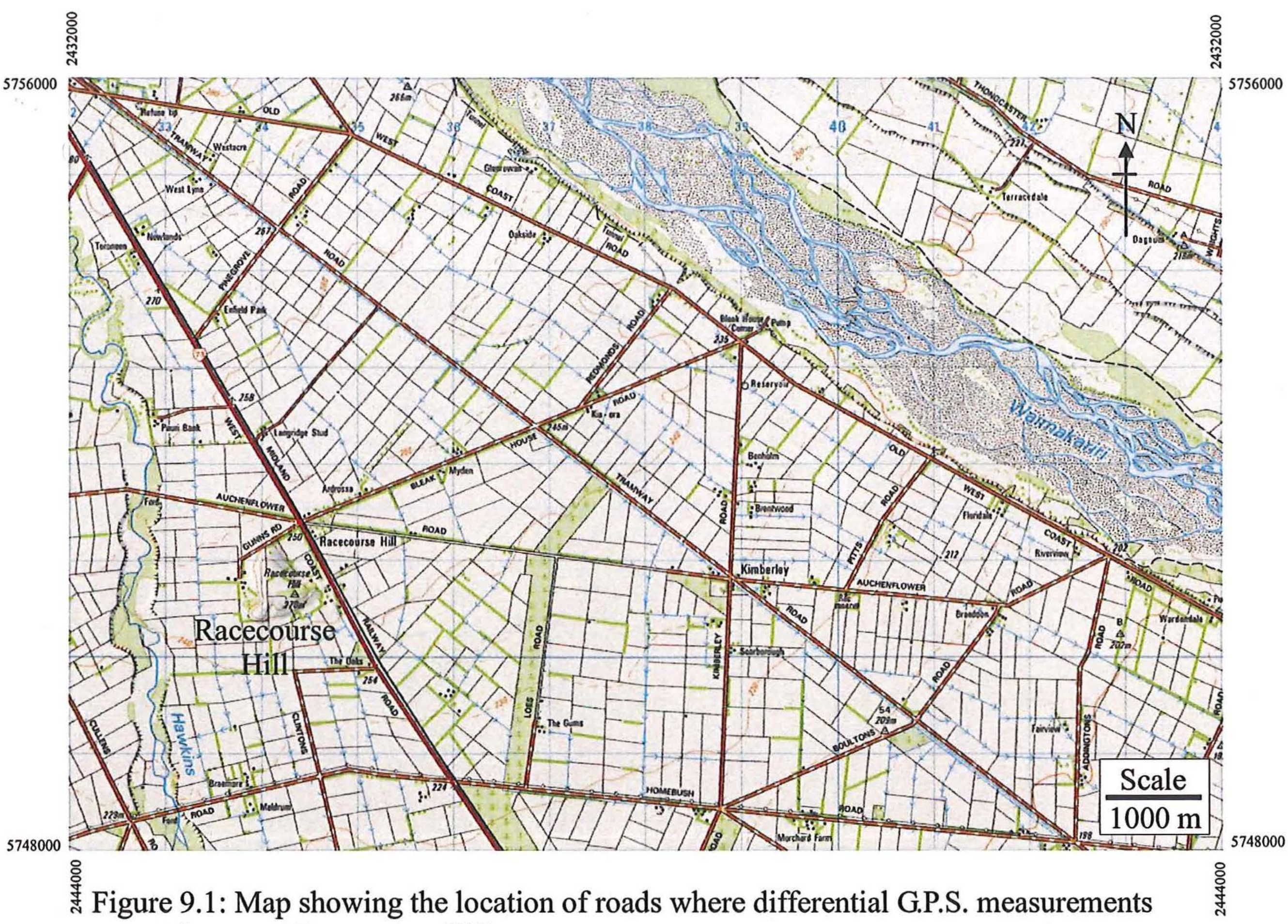


Figure 9.1: Map showing the location of roads where differential G.P.S. measurements were taken near Racecourse Hill.

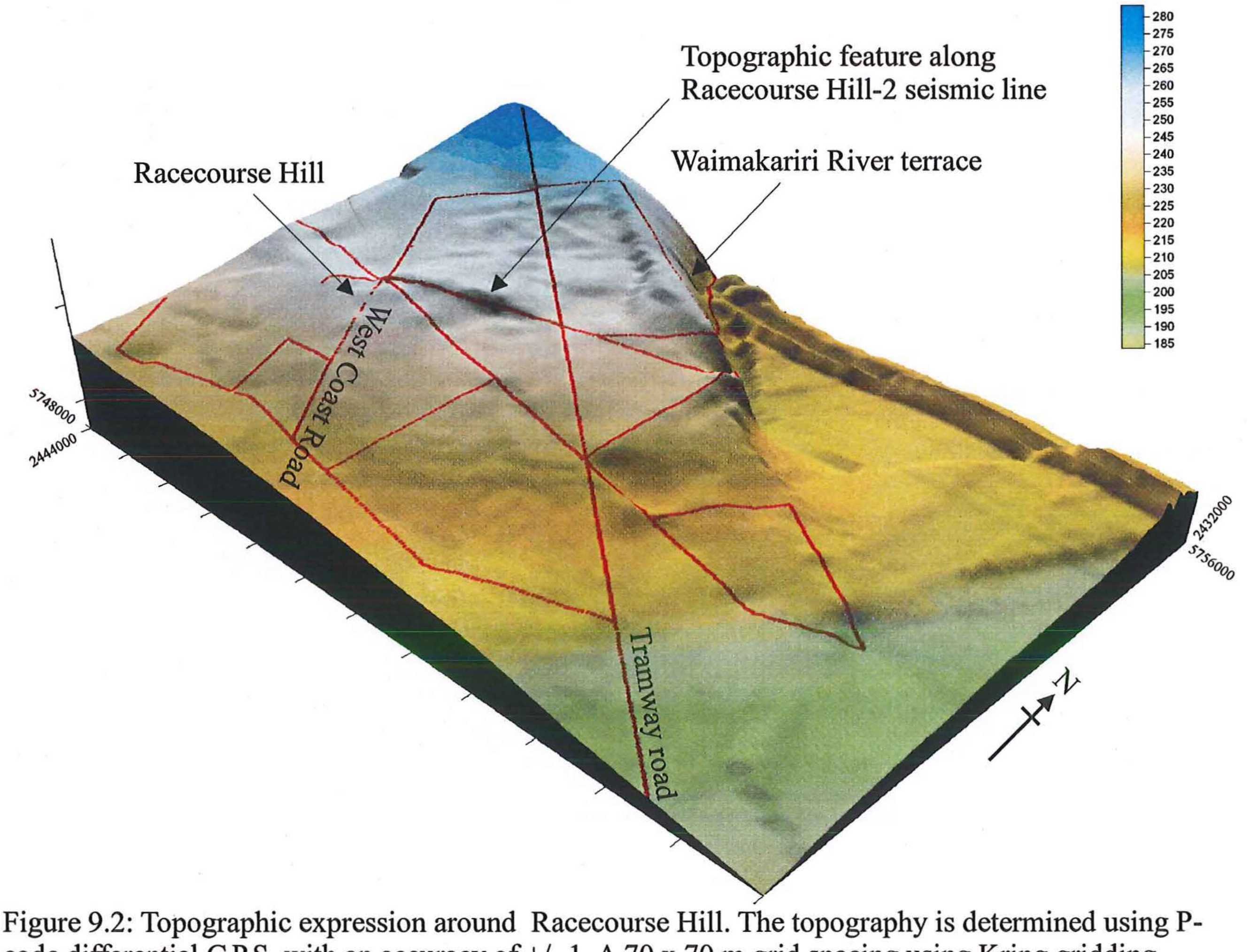


Figure 9.2: Topographic expression around Racecourse Hill. The topography is determined using P-code differential G.P.S. with an accuracy of +/- 1. A 70 x 70 m grid spacing using Kring gridding algorithms was used to produce the topographic model . Red lines show G.P.S. track.

9.5. Burnt Hill and Pines Beach Topography:

No topographic surveys were undertaken at Burnt Hill or Pines Beach. At Burnt Hill the topographic elevation variations along the two roads are estimated at less than 2 m along the seismic line length. Topography for the Burnt Hill area is modeled from the New Zealand topographic database NZMG 260. These data have 20 m photogrammetrically defined contours with interpolated contours every 10 m. These data are then used to define the three-dimensional topographic model of Burnt Hill seen in Figure 9.3. The coastal beach setting of Pines Beach means that there is effectively no topographic elevation changes along the seismic line.

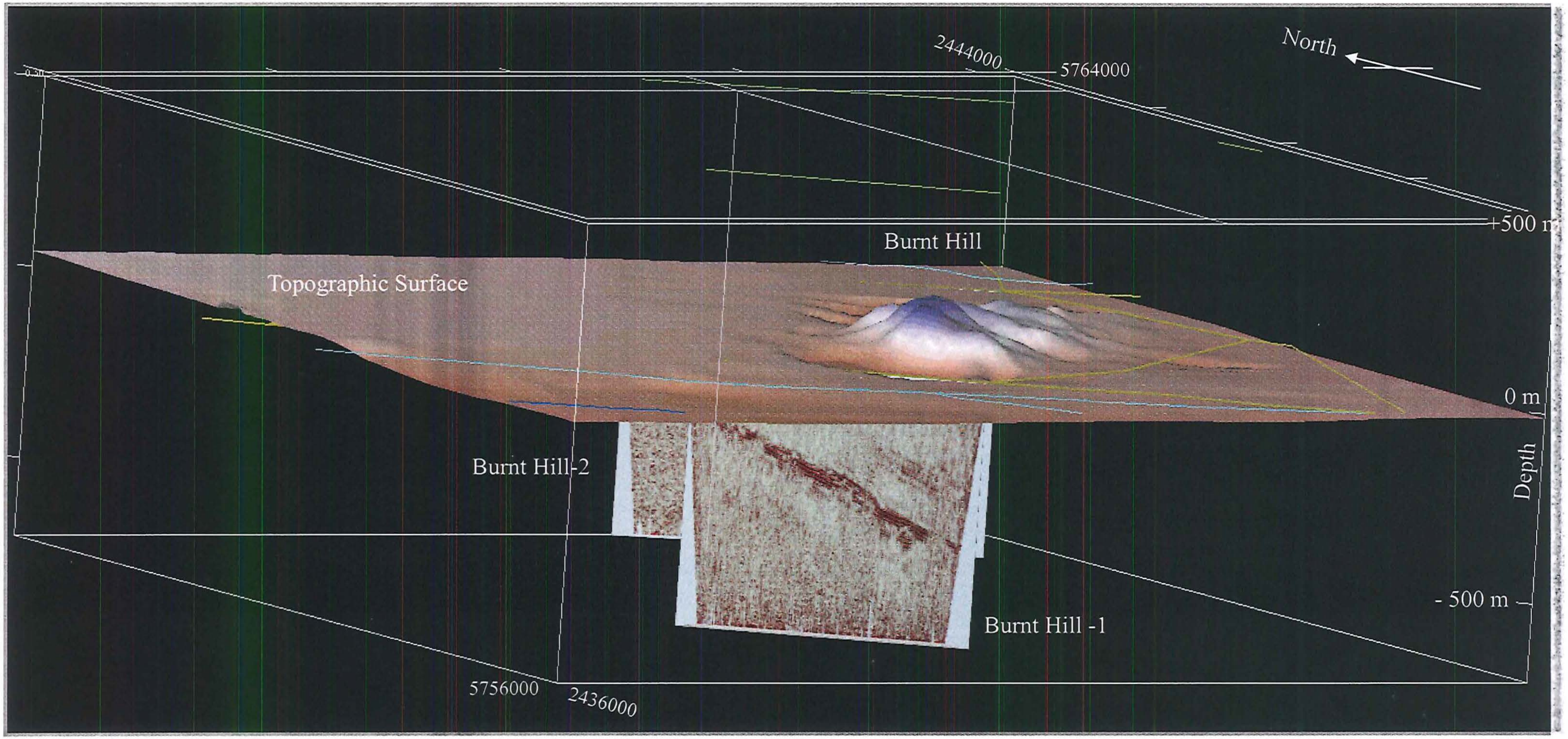


Figure 9.3: Seismic reflection sections Burnt Hill-1 and Burnt Hill-2 shown in their correct geospatial position. Two way time has been converted to depth using a constant 2000 m/s interval velocity. New Zealand NZMG 260.

Chapter 10. Survey Results

The aim of this chapter is to describe the results obtained from the seismic reflection surveys, borehole logging, and topographic surveys undertaken in the three field areas.

10.1. Racecourse Hill results:

10.1.1. Racecourse Hill Seismic reflection results:

Racecourse Hill-1 and Racecourse Hill-2 seismic surveys were designed to image paleo-fluvial architecture including paleo-channels and cut-and-fill valleys associated with the paleo-Hawkin and paleo-Waimakariri River Late Quaternary cycles of incision and aggradation. Prior to this study it was believed that groundwater resources in the area were likely to be concentrated within these zones (Warburton, 1996b, a; Warburton et al., 1996). The two seismic reflection surveys undertaken at Racecourse Hill have provided very different results, and so will be discussed separately. The final processed stacked sections for the two seismic reflection surveys are shown in Figures 10.1 and 10.2 with overlays showing the interpretation.

10.1.1.1. Seismic reflection line Racecourse Hill-1:

The processed stacked section for Racecourse Hill-1 shows almost no reflector packages, and what is present is discontinuous and chaotic except for several strong reflectors (50 – 100 ms TWT) which may represent a deep water table (> 97 % saturation) and a hint of a possible deep reflector (> 300 ms TWT). A range of seismic processing algorithms were applied to the data in an attempt to improve the final stacked section, including F-K filtering, pre-stack trace addition, time variant frequency filtering, and a range of gain and frequency filtering. On the frequency filtered shot gathers reflectors appear to be present but after processing appear to be very discontinuous features.

10.1.1.2. Seismic reflection line Racecourse Hill-2:

The processed stacked section for Racecourse Hill-2 shows a complex seismic reflector image. Three major structures are present along the seismic section.

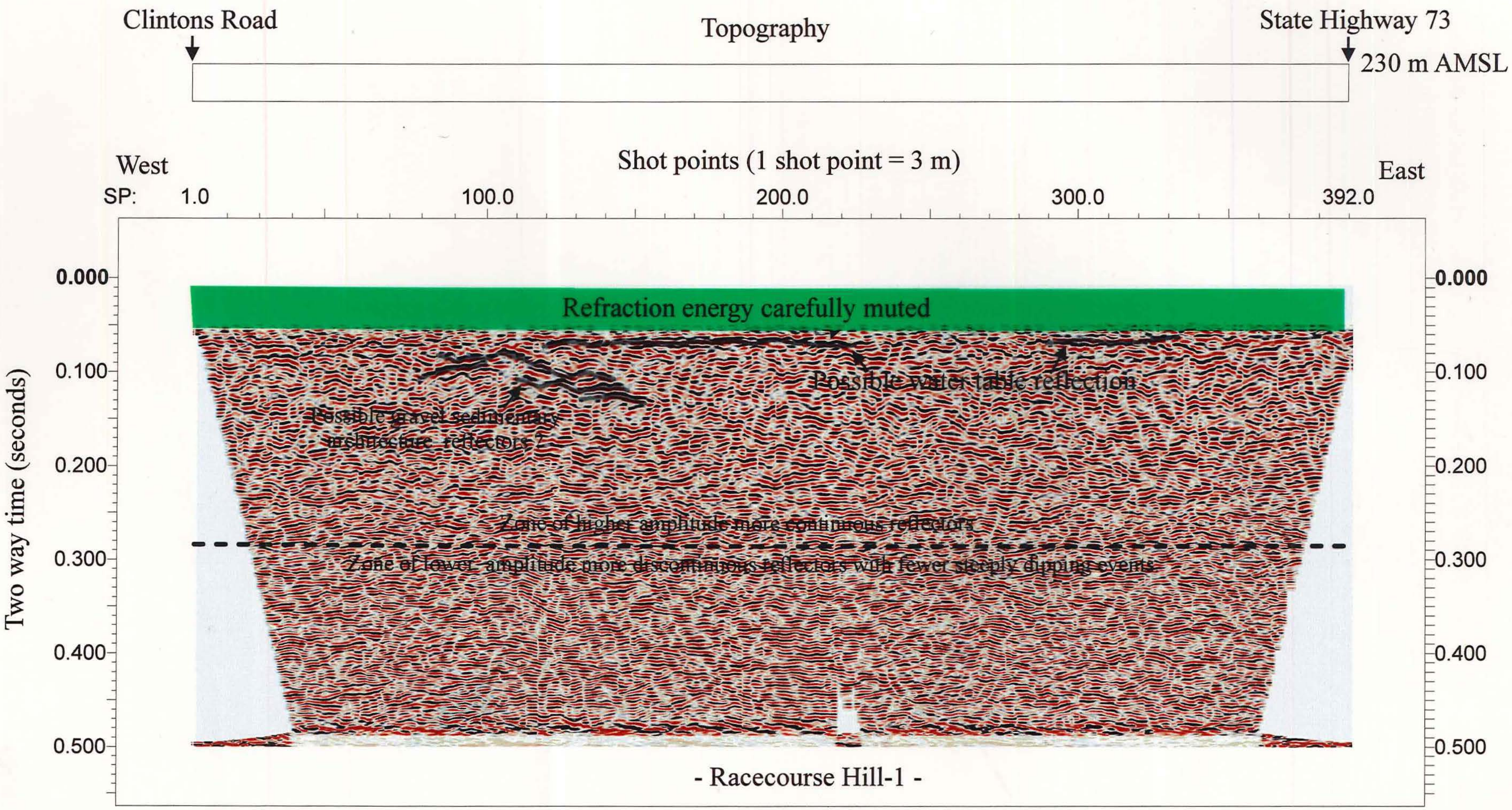


Figure 10.1: Final seismic section for Racecourse Hill-1. Interpretation of the seismic section is shown on the overlay . Vertical exaggeration 1.5:1.

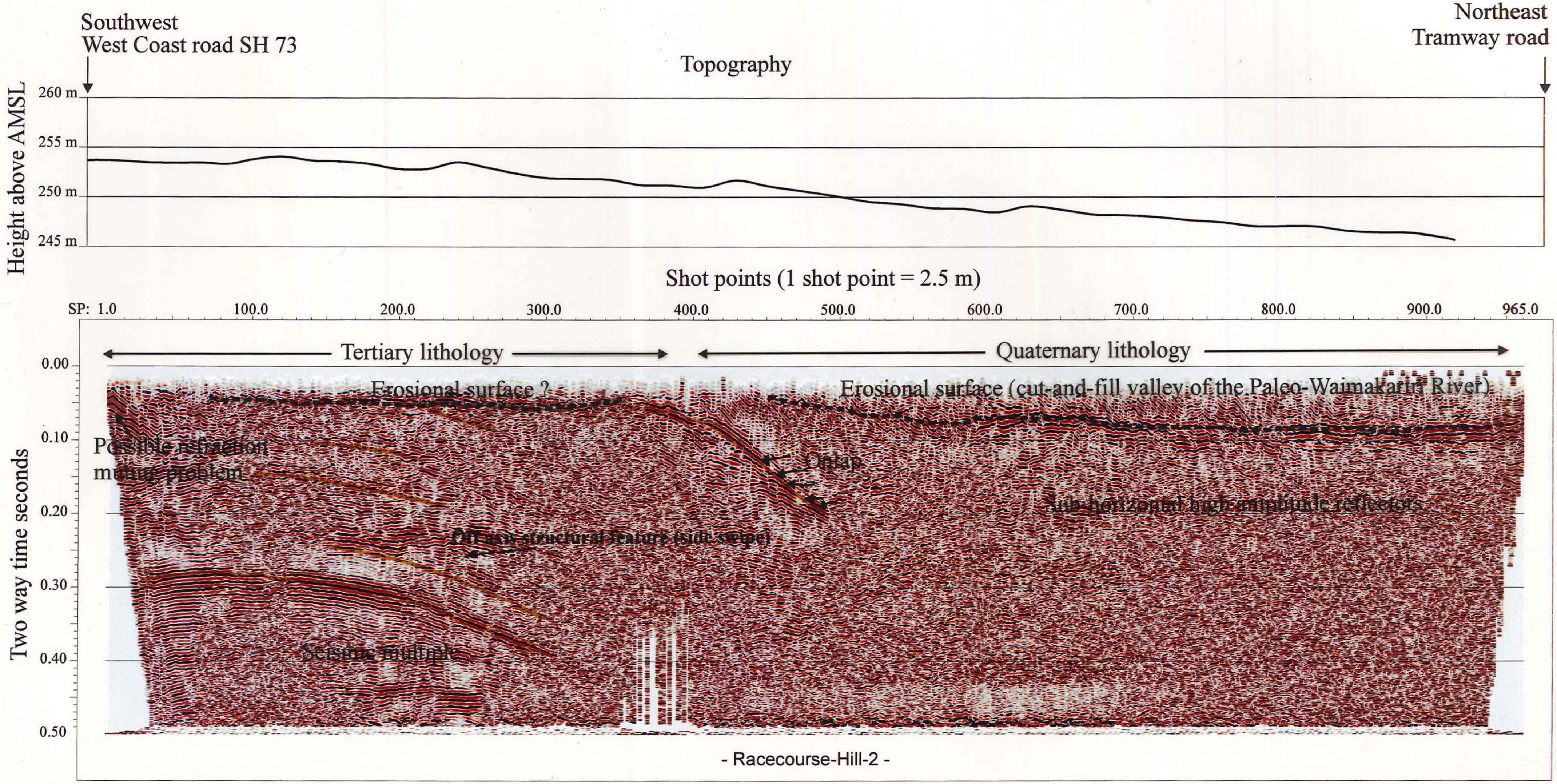


Figure 10.2: Final seismic section Racecourse Hill-2. Intepretation of the seismic section is shown on the overlay . Vertical exaggeration 1.5:1.

1. Two steeply dipping events (26 ° northeast apparent) at SP 400 and SP 250 which appear to be correlated with minor topographic highs. At depth (≈ 200-250 ms TWT) the two northeast dipping reflectors flatten and appear to become horizontal. The dipping events seen below the main reflector at SP 250 are not multiples of the main reflector as they are dipping at similar angle, showing no increase in dip with depth as would be expected for a normal seismic multiple.
2. A more gently northeast dipping strong reflector package that appears to onlap the more steeply dipping feature at SP 400-500. This reflector is undulating and has a different seismic facies above and below.
3. A series of strong deformed, anticlinal reflectors from SP 1-300 (80 – 400 ms TWT). The reflectors appear to be dipping to the northeast and have a maximum apparent dip of 22 °. They appear to represent a large scale structure and are assumed to be Tertiary lithologic units which deformation has brought close to the surface. Some incision has occurred into the surface and the topographic anomalies along the surface may represent zones of differing lithologies, some of which are less indurated and erodable.

The reflector package seen between SP 120-250 (400 ms TWT) is believed to be a multiple of the strong event at 250 ms SP 120-250 (200 ms TWT). The multiple has similar geometric character and dimensions, and is located at a two way time of exactly twice the reflector package above.

10.1.2. L35-742 logged water well results:

After completion of the seismic reflection surveys a water well (L35-742) was drilled at the location shown in Figure 8.2. This well was logged by J. Grindey under directions from the author. The simplified stratagraphic and photographic log from the well is shown in Figure 10.3. The log shows that there is a change in lithology at 62 m from unweathered tightly packed clay and silt bound Torlesse clast gravel to more weathered (dark brown) more tightly packed clay and silt bound Torlesse gravel. This correlates with the seismic reflector seen in the seismic section Racecourse Hill-2 (Figure 10.2). The zone at the base of the unweathered gravels is also found to be the most productive for water, with an estimated production value of 350 l/m.

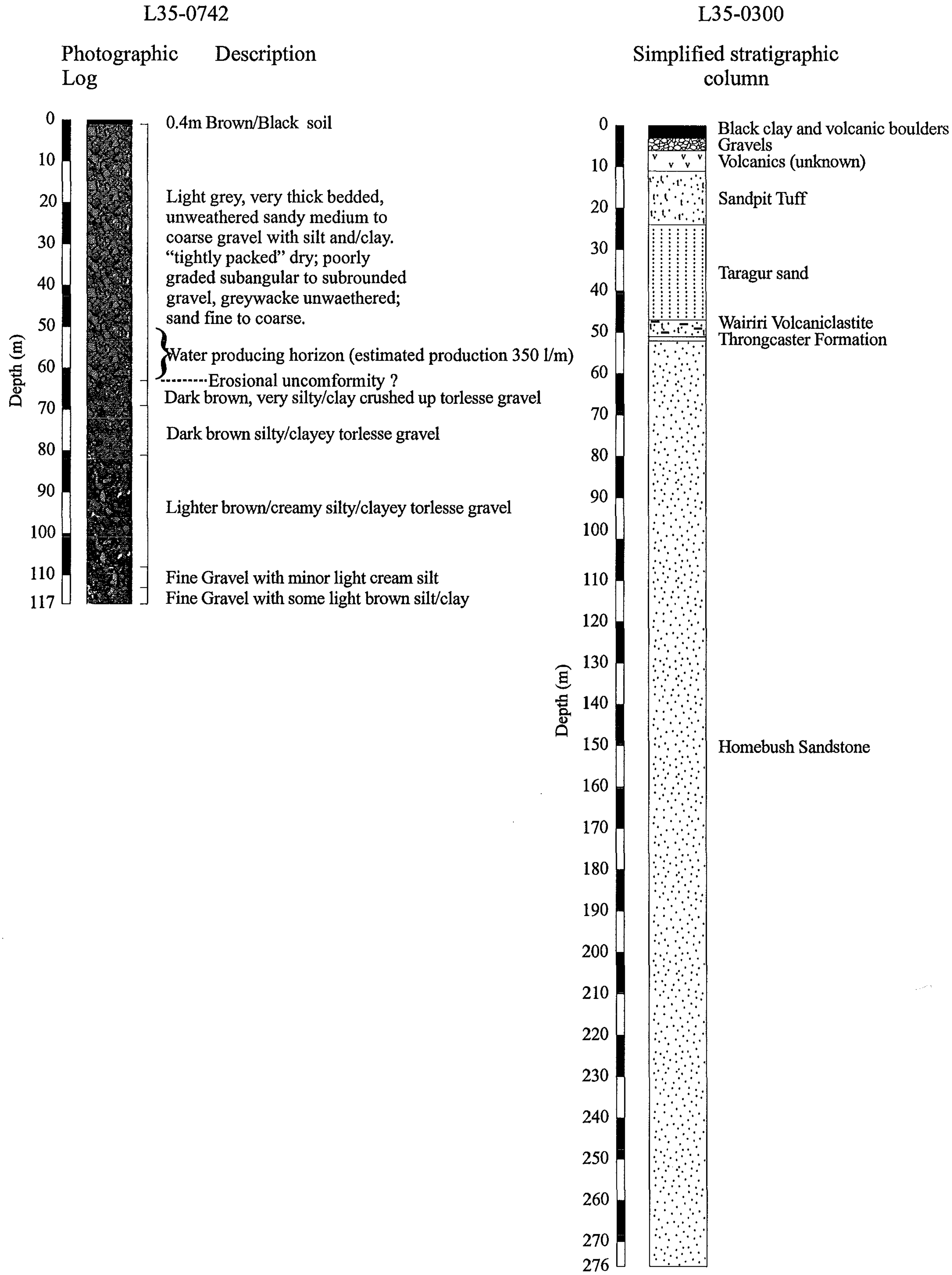


Figure 10.3: Stratigraphic column and photographic log for well L35-0742 and borehole L35-0300.

10.1.3. Geomorphic Analysis:

Analysis of the topographic and geomorphic data (Figure 10.4) around the Racecourse Hill structure is approached with caution. The accuracy of the topographic data collected along the roads has already been defined previously, and is reproduceable (several lines were measured going in both directions), but individual data points are very sparse. Correlating topographic features from one line to the next is difficult due to the distances between features and the lines, but several key results are evident:

1. The area to the northwest of Racecourse Hill is over 100 m higher than the area to the southeast (0.63 degree slope).
2. A topographic high related to Racecourse Hill is present around the obvious Racecourse Hill structure and it appears to be many times larger than the surface expression of Racecourse Hill.
3. This topographic high appears to either warp around the northwest side of the Racecourse Hill, or may be the point at which the topographic high is defined.
4. No surface (or very near surface) paleo-channels are seen to the north of Racecourse Hill but to the west paleo-channels of the Hawkins River can be seen in the seismic data.
5. Along Bleakhouse Road no channels are seen closer than 1 km to Racecourse Hill.

10.2. Burnt Hill Results:

10.2.1. Seismic reflection lines Burnt Hill-1 and Burnt Hill-2:

The Burnt Hill-1 (Figure 10.5) and Burnt Hill-2 (Figure 10.6) seismic profiles show good reflection energy down to depth of >500 m. The two seismic profiles have reflector geometry which is markedly different and shows a very different subsurface stratal geometry. The seismic profile to the north (Burnt Hill-1) has a horizontal, continuous strong reflector with minor undulations at an approximate depth of 300 m, and with several different seismic facies between the surface and this reflector. The seismic profile (Burnt Hill-2) to the south of Burnt Hill has a strong east dipping (dip 14° apparent) reflector with several different associated seismic facies.

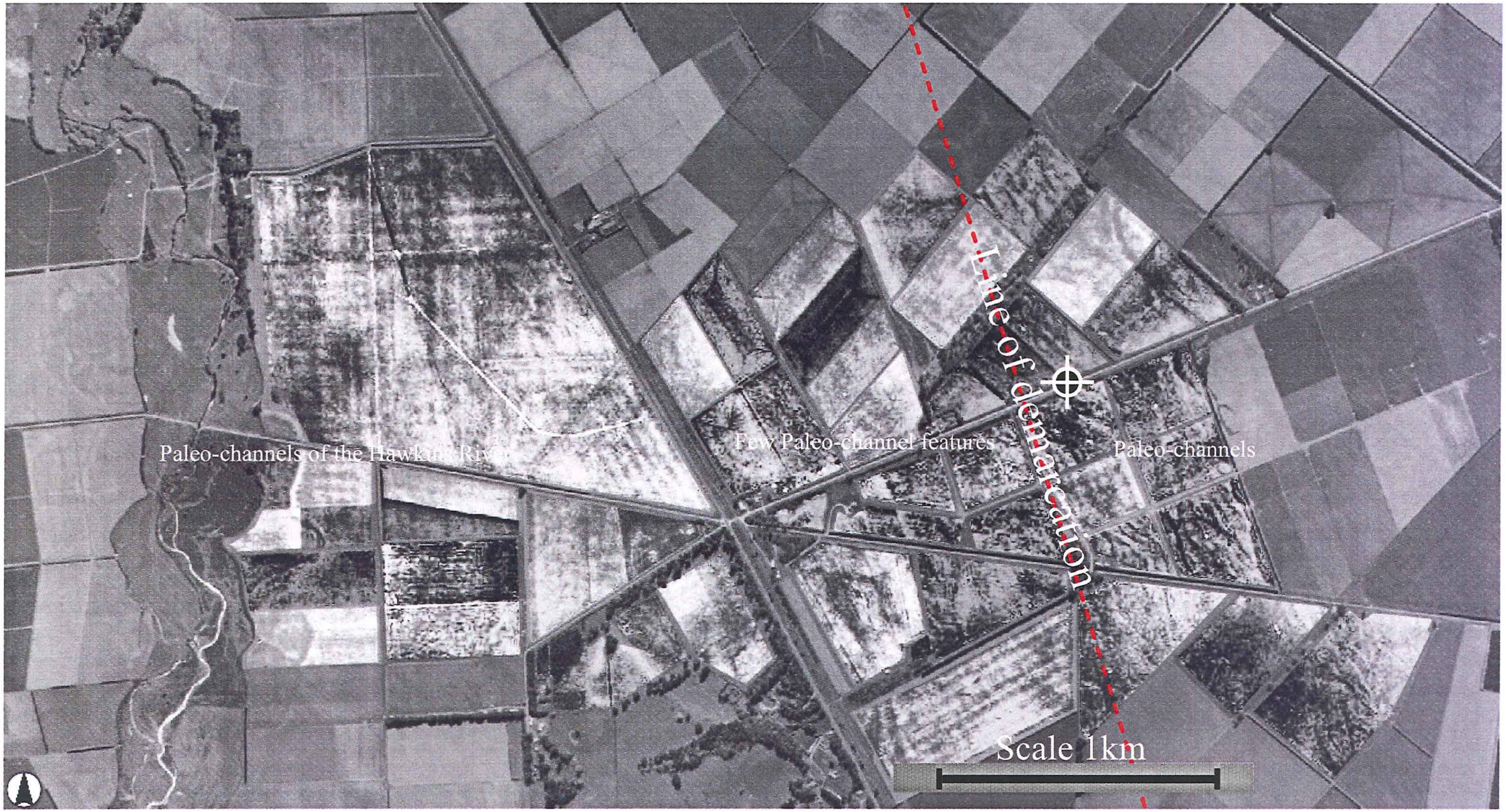


Figure 10.4: Aerial photograph of Racecourse Hill with contrast enhanced to bring out paleo-channels and structural detail. Digital raster data supplied by Environment Canterbury.

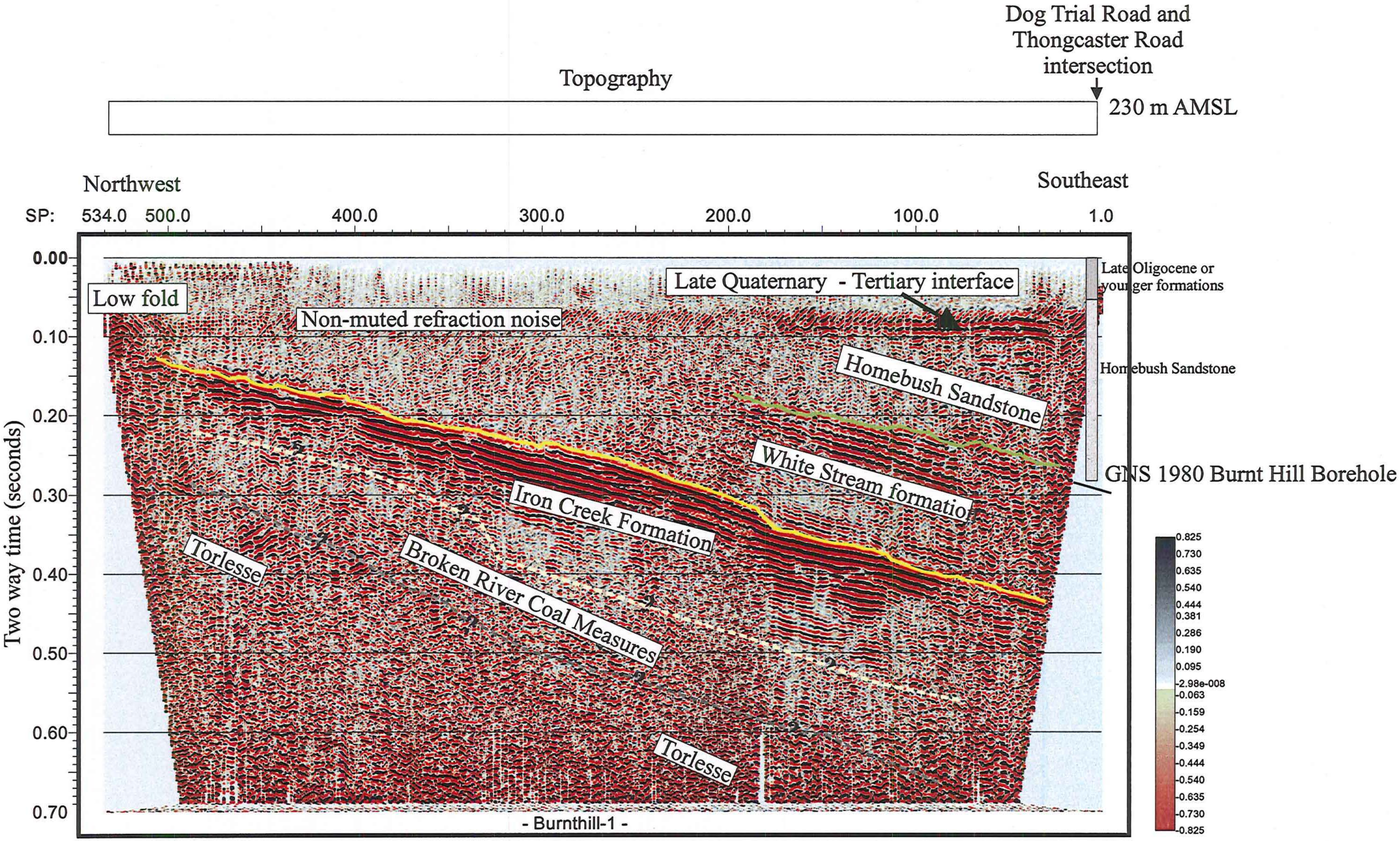


Figure 10.5: Interpreted seismic section Burnt Hill-1 with DSIR 1980 borehole (L35-0300) shown. Vertical exaggeration 1.5:1.

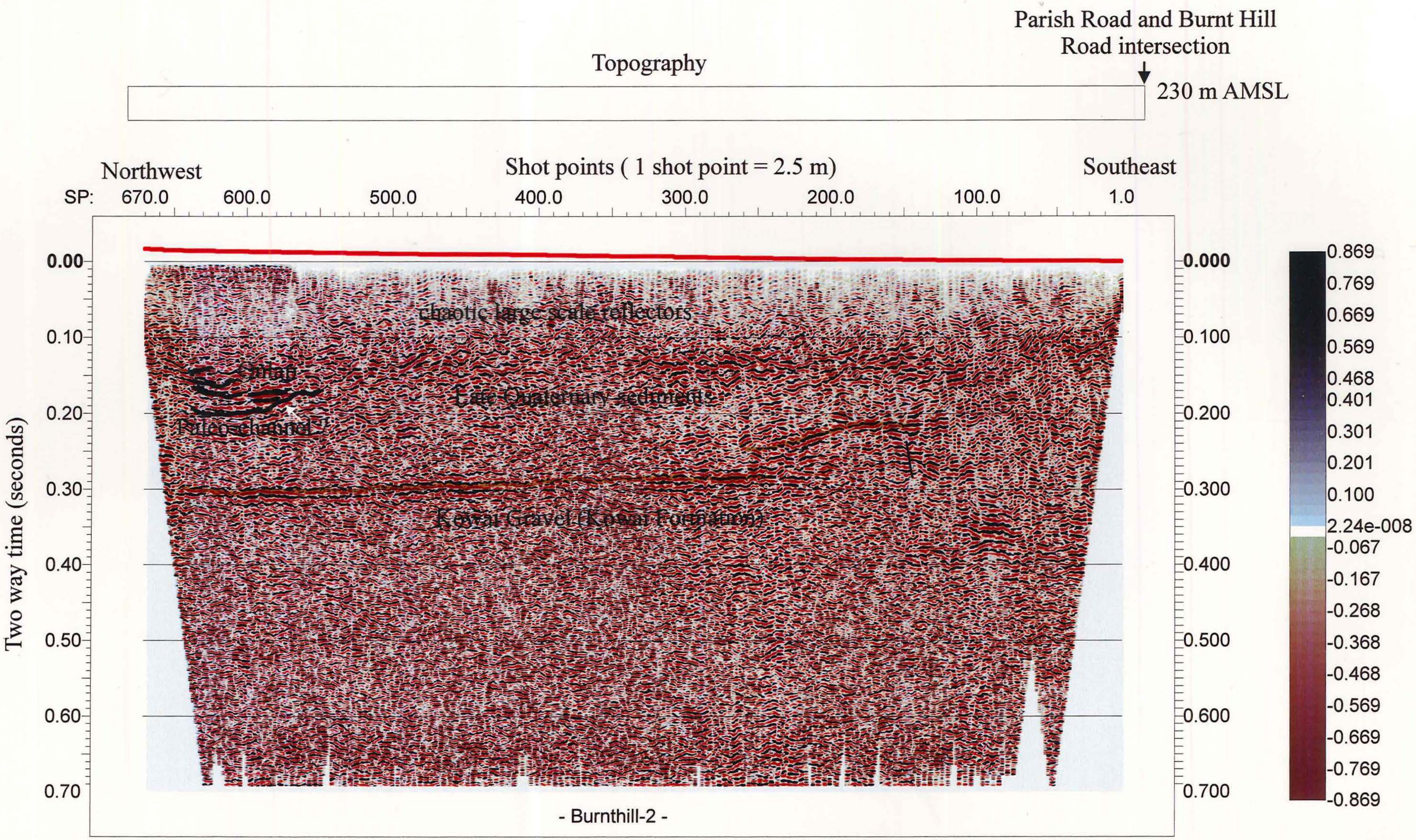


Figure 10.6: Processed seismic section Burnt Hill-2 with overlay showing interpretation . Vertical exaggeration 1.5:1.

10.2.2. Geomorphic analysis:

Geomorphic analysis of surface drainage from aerial photography indicates that the Waimakariri River has flowed to the south of Burnt Hill since postglacial incision commenced (Figure 10.7). Since the end of the last glacial maximum the Waimakariri River has undergone incision into the older Waimakariri braidplain surface (Brown et al., 1988). This down-cutting has resulted in a series of abandoned terraces (5 –20 m in height) flanking either side of the present Waimakariri River channel. A series of degradation terraces can be delineated running to the southwest of the Hill, which indicates that the Waimakariri Rivers flow direction has been controlled by the inlier since at least the end of the last glacial. Geomorphic drainage patterns around Burnt Hill also indicates that in general the drainage has been from the northwest to the southeast and mainly consists of paleo-braidplain deposits (Figure 10.7).

10.3. Pines Beach results:

10.3.1. Pines Beach seismic reflection results:

The relatively small maximum source-receiver offsets (46 m) when using the towed geophone array mean that is tailored for the very shallow depths (0 - 100 m) (Figure 10.8). The towed array images below this depth, but the reduced normal moveout of reflectors results in inaccurate depth conversion using velocity analysis (Yilmaz and Doherty, 1987). Velocity analysis indicates that the stacking velocities are generally 1400 m/s from a TWT of 30 ms and only increase slowly with increasing depth. This is believed to be the cumulative result of; i) the reduced compaction in the saturated (possibly overpressured pores of the sediments), ii) the inherent low seismic velocities in estuarine/marine silts, peats and muds which are believed to underlie the survey site (Brown, 1998) and iii) the inaccuracy in NMO corrections at later two way times due to the small source-receiver offsets.

The top 200 ms (160 m) of the subsurface has been clearly defined. The vertical resolution of the survey is ~1.6 m, with many very small-scale reflector packages present. A strong reflector is seen at 30 ms TWT (21 m) with further strong reflectors down to 80 ms TWT (49 m). The reflectors within this zone appear to be continuous across the section with very low angle onlapping reflectors. In between the strong continuous reflectors are packages of small scale sigmoidal reflectors which at several locations downlap onto the lower more continuous reflector and toplap to the continuous reflector above. A zone is then present which shows less continuous large scale hummocky and complex to discontinuous reflectors.

Figure 10.7: Aerial photograph of Burnt Hill with contrast enhanced to bring out paleo-channels and structural detail. Digital raster data supplied by Environment Canterbury.

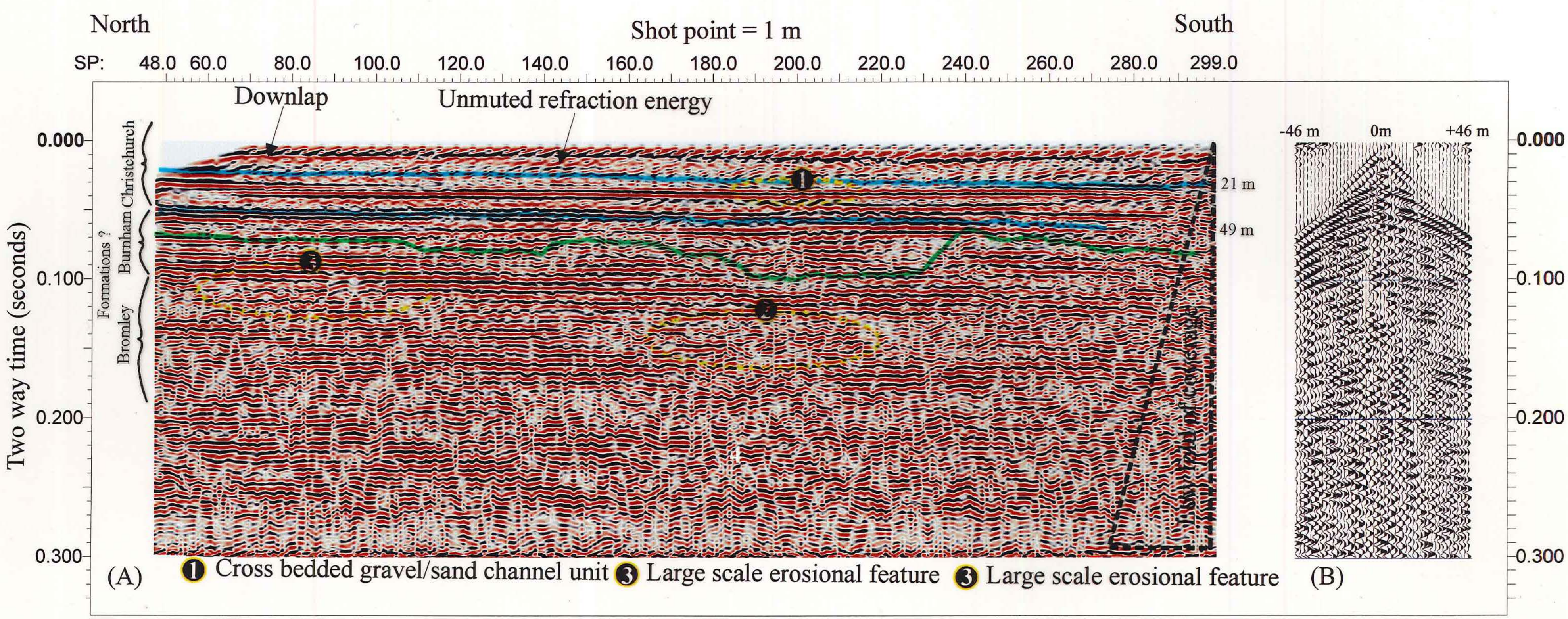


Figure 10.8: (A) Intepretation of the Pines Beach processed seismic reflection line. (B) Singe shot gather from the centre of the Pines Beach seismic line. The earliest clearly defined reflector is 30 ms TWT.

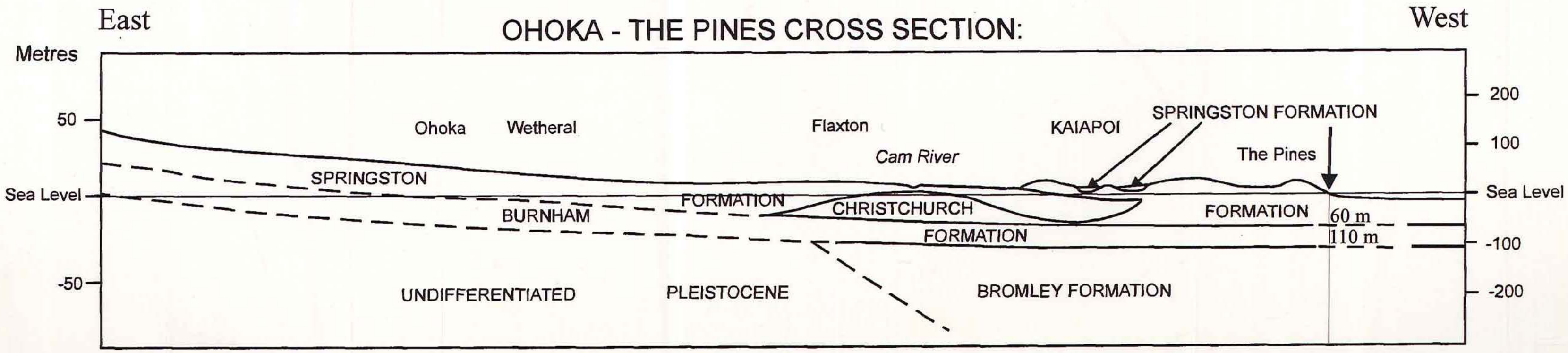


Figure 10.9: Pines Beach cross section from Ohoka to Pines Beach. Location of Pines Beach Seismic Line is shown by arrow. The seismic line is perpendicular to the cross section. From Brown L.J. 1973.

Chapter 11. Synthesis

The aim of Chapter 11 is two fold, i) to present the authors' interpretation of the seismic reflection survey and associated data, and ii) to assemble the disparate results from the surveys undertaken on the north Canterbury Plains and to resolve and synthesize what can be learnt from the seismic reflection, topographic, geomorphic analysis with respect to the determination of hydrologically important geologic structures. The results from each field area are covered sequentially and all available data is used to develop a subsurface model for each area.

11.1. Racecourse Hill:

11.1.1. Racecourse Hill-1:

The Racecourse Hill-1 survey shows that a structural boundary is present adjacent to the seismic line. Previous drilling (ECan, 2004) indicates that this location has over 255 m of largely clay bound gravels, which elsewhere in north Canterbury have offered a good seismic target. A possible explanation for the lack of seismic character seen in this profile is that the area to the east of Racecourse Hill has either had a large amount of accommodation space generated rapidly enough that sedimentary processes have not had enough time to generate much lithologic detail during deposition or that existing accommodation space has been rapidly infilled.

Two interpretations are possible for the seismic section Racecourse Hill-1.

1. The seismic reflection character present in the section represents an extremely complex sedimentary architecture with reflectors having only minor (<100 m) lateral continuity; or
2. Seismic reflection penetration is limited in this location or seismic reflection surveying was not successful at this location due to near surface conditions (depth of water table, near surface velocity inversions) and the seismic section is just a processing artifact.

The results indicate that in either case the subsurface characteristics differ from many of the other locations in north Canterbury where seismic reflection surveying has been successfully undertaken. The second interpretation does not appear to be the correct one, as traces of discontinuous reflectors are present on the processed seismic section, indicating that seismic reflection energy is present. Also, the two sources used have been successful elsewhere in north Canterbury, even in unconsolidated unsaturated gravels which are likely to represent the end member in the application of seismic reflection surveying. Even with the more powerful seismic source the signal is not improved. Elsewhere in the north Canterbury plains area (Finnemore and Pettinga, 2000) a similar lack of coherent reflectors is seen in the near surface, but more continuous reflectors are seen below the chaotic reflector facies indicating that the seismic energy has penetrated below the chaotic facies and has not been absorbed.

11.1.2. Racecourse Hill-2:

A structural and sedimentary model for the Racecourse Hill area based on seismic reflection, topographic and geomorphic analysis has been defined. The structural feature underlying Racecourse Hill must uplift Tertiary units to the near-surface, as glauconitic sand has been seen in a well (L35/0323) drilled at the far southwest of the seismic line Racecourse Hill-2 (Figure 8.2). The seismic line is parallel to the inferred regional structural grain (Cowan, 1992; Pettinga and Armstrong, 1998; Pettinga et al., 2001), and appears to run longitudinally along the inferred axial trace of a fold in the subsurface, with an inferred plunge to the northeast. It is assumed that the strongly dipping reflectors at depth on the southwest end of seismic line Racecourse Hill-2 represents a tectonically controlled structure, which has caused warping of the Tertiary age lithologies. Above this structure the deformation continues but shows a more chaotic appearance. This is likely to represent the Mt Brown or a similar lithologic formation formed in a higher energy depositional environment. Above this deformation a set of generally slightly steeper dipping reflectors, with cross-cutting events truncating and inter-fingering with the dipping events. At between 200-250 m the reflectors flatten out and a reflector is present at $\approx$ 230 m.

From borehole L35/0742 (Figure 8.2 and Figure 10.3) it is known that gravels are present to 117 m in at least one location along Bleakhouse Road and that a major change in lithology occurs at 60 m. It therefore appears that the dipping reflector represents an erosional unconformity between an older gravel horizon and a new gravel sedimentary unit.

It is believed that a series of incision's caused by fluvial avulsion of the paleo-Waimakariri as it avulsed from the northeast-southwest has resulted in a series of buried paleo-river terraces which can be seen in seismic line Racecourse Hill-2. The presence of several terraces indicates that the avulsion of the river occurred during several episodes in the Late Quaternary. The fact that a terrace is visible to the southwest of the second terrace indicates that at a later period a second incision occurred but was not as laterally extensive, or that the paleo-channel had moved to the northeast. It appears that the avulsion of the paleo-Waimakariri has been pinned by the Tertiary age structure underlying Racecourse Hill.

11.2. Burnt Hill:

Several inferences can be made concerning the Burnt Hill structure and geometry

1. The former NZ Geological Survey borehole (N33-0300) completed in 1980 is believed to have been only 10's metres from penetrating the next lithologic horizon. Based on the stratigraphic framework of McLennan (1981) and the fact that the Broken River Coal measures can be ruled out as the underlying lithology as no strong angular unconformity is seen in the reflection data, it is believed that the White Stream Formation is the underlying formation.

2. The Burnt Hill basaltic lava capping does not appear to continue in the subsurface buried beneath the Pliocene and Pleistocene gravels to the east of Burnt Hill as no strong reflector is seen in further seismic survey undertaken to the east of Burnt Hill (Finnemore and Pettinga, 2000). This may indicate that the material has been eroded by the paleo-Waimakariri or the structural geometry of Burnt Hill is more complex than just a simple singular back thrust.

3. Burnt Hill is the surface expression of a much larger tectonically controlled structure of this area of the Canterbury Plains and may be a back thrust of the Hororata-Springbank fault system.

11.3. Burnt Hill-Racecourse Hill area:

The seismic sections for the Racecourse Hill and Burnt Hill areas indicate that the two inliers are structurally controlled elements that have not been eroded. It appears that the paleo-

Waimakariri has eroded a paleo-channel much further to the southeast than the present erosional channel. It is believed that the present channel has been down-cutting since the end of the last glaciation (14 kyr). This would imply that the channel has formed during previous glacial episodes and migrates through time, as the plains are believed to have aggraded during the late stages of glacial periods. The work of Bal (1996) indicates that a high hydraulic conductivity pathway exists across the plains to the south of the present Waimakariri River channel, and this is supported by the paleo-fluvial architecture seen in the Racecourse Hill seismic reflection surveys.

11.4. Pines Beach seismic reflection survey:

Based on the Bexley borehole stratigraphy the Pines Beach reflection survey is believed to show two major episodes in the sedimentary history of this part of the Canterbury plains (Figure 10.9).

A sample taken from the Bexley borehole at 37.3 m has been dated based on pollen assemblage as Early Holocene (Oxygen Isotope Stage 1, Christchurch Formation) (Brown, 1998). Assuming that the prograding coastline seen at the Bexley borehole site is similar to the more northern Pines Beach location, the top 21-49 m section in the Pines Beach survey is assumed to be Holocene age sediments that have not been eroded due to the subsidence of the southern part of Pegasus Bay 0.25 m/ka (Brown et al., 1995) and the protection afforded by Banks Peninsula to the erosive southerly swells. The continuous reflectors with only minor undulations are assumed to be basin or locally extensive aggradation events such as overbank deposits from flooding, or rapid eustatic sea level rises or tectonic subsidence events. The small-scale units seen between the more continuous reflectors appear to be from a higher energy environment and may represent avulsion and deposition of channel bars forming a sequences of laterally migrating sigmoidal (in cross-section) reflectors (5 m in height, and extending over 7 m laterally).

Below this zone the reflectors become more discontinuous and irregular. Several large-scale reflector packages can be seen which appear to be erosional channels (~70 m across ~20 m deep) with onlapping sediment infilling the channels. This is assumed to represent a period of coastal fluvial erosion possibly during an earlier interglacial event (Browne and Naish, 2003).

Chapter 12. Conclusions

The aim of chapter 12 is to summarise the results and interpretations for the research undertaken on the North Canterbury Plains, and to describe the conclusions reached on the use of seismic reflection surveying for delineating hydrologically important geologic structure. The chapter also includes recommendations for future research.

12.1. General conclusions:

The seismic reflection surveys undertaken in the northwestern Canterbury Plains demonstrate that shallow seismic reflection surveying can delineate sedimentary architecture within the Quaternary sediments and resolve the underlying Cenozoic (bedrock) lithologies to a depth of 500 m using hammer and plate and mini-Sosie© seismic sources. The Late Quaternary sedimentary architecture appears to be more complex, and larger-scale than the sedimentary architecture seen in the Late Quaternary sediments of the Omihi Valley. The seismic reflection surveys indicate that the structure below the north Canterbury Plains is complex. In isolation the seismic reflection surveys only marginally improve the structural model for the Plains, but offer an initial opportunity to evaluate the usefulness of shallow high resolution seismic reflection surveying for more detailed, targeted studies of the active tectonic deformation when combined with surface tectonic geomorphic mapping.

12.2. Stratal and structural conclusions:

12.2.1. Racecourse Hill and Burnt Hill:

The usefulness of the seismic reflection lines undertaken near Racecourse Hill (Racecourse Hill-1 and Racecourse Hill-2) in delineating the subsurface tectonic controls on structural deformation is limited due to the location and extent of the lines. The seismic lines were undertaken to locate large-scale paleo-fluvial channels between the present Waimakariri River and the Pre-Quaternary bedrock cored foothills to the southwest and orientated perpendicular to the present Waimakariri River. The lines were therefore orientated parallel to the inferred strike of deformation and faulting (McLennan, 1981; Cowan, 1992; Pettinga and Armstrong, 1998; Jongens et al., 1999; Finnemore and Pettinga, 2000; Estrada, 2003). The seismic reflection line Racecourse Hill-2 shows a complex and deformed subsurface geology, which appears to show that the small surface expression at Racecourse Hill is a part of a much more extensive tectonically controlled structure. Whether this structure is linked with the nearby Hororata Fault Zone can not be addressed by the surveys undertaken, but the location of Racecourse Hill and its general alignment with the Hororata Anticline, Burnt Hill and Starvation Hill are indicative of a through-going fault system. Racecourse Hill may therefore be an extension of the Hororata Anticline structure to the south, and in fact represent the termination of this structure as it plunges to the northeast. This structural model is supported by the strongly dipping reflectors seen at the southwestern end of seismic reflection line Racecourse Hill-2 and the horizontal layered gravels filling the subsurface from 30 - 300m on the northern end of the line, which may represent a cut-and-fill paleo valley of the Ancestral Waimakariri River. More detailed structural interpretation here is not warranted given the limitations of the seismic lines completed.

Several other important conclusions can be drawn from the survey results from Burnt Hill and Racecourse Hill, including:

- The Late Quaternary sedimentary thickness to the north of Burnt Hill is > 300 m.
- Tertiary age strata are not seen near the surface to the north of Burnt Hill
- Tertiary age strata are not recognised in seismic sections to the east of Burnt Hill.
- No major fault is seen in the seismic reflection line Racecourse Hill-2 to the north of Racecourse Hill.
- No coherent large scale sedimentary architecture features are seen in the southern seismic reflection line Racecourse Hill-1.

The Burnt Hill and Racecourse Hill structures recognized from both surface expression and seismic reflection surveying indicate that these two structures do not align directly along the same northeast-southwest trend, but are offset from each other. This implies that a structural step-over exists at depth, with fault displacement transfer occurring, and leading to a structural saddle may have provided a location for the Waimakariri River to more easily maintain and develop its erosional channel.

12.2.2. Pines Beach:

The Pines Beach survey seismic penetration (< 200 m) is such that no tectonic implications can be drawn, but within the limited area of investigation no faulting or structural deformation can be determined.

12.3. Implications for groundwater resources, Racecourse Hill and Burnt Hill :

The work of Soons and Gullentops (1973), Wilson (1989) and Suggate and Clapperton (1990) has shown that the Quaternary gravels of the Canterbury Plains formed during glacial periods when braided rivers with high sediment load avulsed across the Plains building large alluvial fans or concave braidplains from low permeability glacial outwash material (refer Figure 2.1). Immediately postglacial and during interglacial times it has been shown (Soons and Gullentops, 1973; Wilson, 1989) that the reduction in sediment load resulted in the rivers having a higher erosive capacity and the initiation of down-cutting into the previously deposited fan surfaces. Due to reworking and sorting by fluvial action the interglacial and postglacial sediments have been shown (Aiken et al., 1994; Salogar and Salvage, 2002) to have a higher permeability than the glacial sediments. This permeability improves to the east resulting in a series of highly permeable gravel units below the present city of Christchurch. The transmisitivity mapping of Bal (1996) indicates that the post-glacial incision depth is dependent on tectonic and eustatic factors, as well as sediment flux, and that during interglacial perios this may result in different incision depths. The work of Bal (1996) also shows that incision is likely to occur in previously incised cut-and-fill valleys generating a series of high transmisivity units (aquifers) with quite variable depths and thicknesses.

The seismic reflection surveys undertaken at Racecourse Hill supports this model of composite braidplain formation during glacial periods and down-cutting during interglacial periods, showing a cut-and-fill valley to the north of Racecourse Hill (Figure 10.2). This appears to represent a possible groundwater resource at the uncomformity (50 – 60 m depth) between the older underlying gravel sediments and younger slightly less clay bound more permeable gravel sediments.

There also appears to be some minor incision into the Early Quaternary/Upper Tertiary sequence adjacent to Racecourse Hill structure (Figure 10.2) which may offer a possible ground water resource, but this would need to be verified by undertaking a three dimensional grid of more detailed shallow seismic reflection lines to delineate the geometry of any paleo-fluvial channels present.

The Burnt Hill seismic reflection surveys show that the subsurface geologic structure is complex adjacent to Burnt Hill and any groundwater model in this area must take this into account. The seismic reflection data indicates that the Late Quaternary sediments to the north are at least 300 m thick and are not deformed. While to the south of the Burnt Hill inlier they are between 100 – 200 m thick and underlain by dipping Tertiary age strata.

It is therefore proposed that the formation of the aquifer units for the east and west Canterbury Plains are contemporaneous) and form during postglacial/interglacial incision and reworking of the glacial outwash sediments. To the east the aquifers are interfingering high permeability fluvial channels forming a laterally extensive gravel/sand unit sandwiched between estuarine, lagoonal muds/clays. To the west the aquifers are high permeability fluvial channels (but with lower permeability then to the east) located within cut-and-fill paleo-valleys filled with low permeability outwash gravels.

12.4. Future research:

The research undertaken during this thesis has established that seismic reflection surveying is successful in the Burnt Hill and Racecourse Hill areas, but is limited by the need for more extensive and integrated geologic, geomorphic and geophysical surveying in the area. Seismic lines undertaken outside such a framework are difficult to interpret and limited in their application to real geologic, hydrogeologic and structural questions. It is therefore proposed that future research should address the development of such an integrated research framework.

12.4.1. Geomorphic mapping:

In 1987 the University of Canterbury Department of Geological Sciences established its Active Tectonics and Earthquake Hazards Research Programme, and this has as a central theme the integrated understanding of the tectonic geomorphic and geological evolution of the Canterbury region, in the context of its location within the active plate boundary deformation zone in NE South Island. Clearly, much useful information on active tectonic deformation can be determined from the geomorphic analysis of the landscape morphology such as abandoned river channels, older erosional/depositional surfaces and stream diversion and gradient analysis (Yousif, 1988; Estrada, 2003). Systematic analysis of the Burnt Hill and Racecourse Hill study sites could determine if there are paleo-geomorphic remnants present in the subsurface of the earlier braidplains, or alternatively if degradational river terraces and channel fill sequences are present. Such features could indicate if the Burnt Hill or Racecourse Hill structures pre- or post-date the onset of mid to Late Quaternary deformation in this area.

12.4.2. Seismic reflection surveys:

Further shallow seismic reflection surveying should be undertaken in across the northwest Canterbury Plains, with a priority survey being a ten-kilometre line orientated northeast-southwest perpendicular to the inferred paleo-drainage of the North Canterbury Plains. The survey should delineate the extent and location of any previous cut and fill valleys within the Late Quaternary sediments ("high" transmissivity channels seen in Bal (1996), and also provide the depth of the Late Quaternary sediments present, and hence identify the potential for unrecognised groundwater resources.

In September of 2003 two seismic reflection lines (each 4 km long) were undertaken, as part of a collaborative project with ETH Zurich looking at fault geometry in an oblique plate convergence tectonic setting. The ETH lead project was unrelated to this thesis research, but was initiated on the success of the Burnt Hill and Racecourse Hill surveys of this study, and used similar acquisition parameters. The ETH seismic reflection lines are parallel to the Waimakariri River to the northwest of the Waimakariri GorgeI. These surveys were based on the success of the Burnt Hill and Racecourse Hill surveys of this study, and used similar acquisition parameters. At the time of writing initial results from these additional surveys indicate that a similar structural style is present to that recorded near Burnt Hill (southeast dipping blocks). To delineate the structural style below the plains in the Burnt Hill and Racecourse Hill area, a continuation of these surveys is needed. This would allow any through-going extension to the Hororata Fault System, fault step-overs and imbricate faulting to be identified. At Burnt Hill the survey along Thongcaster Road should be extended further southeast to map the Harper Hills Basalt as it dips to the southeast.

12.4.3. Alternative geophysical methods:

The Tertiary age basaltic flows present in outcrop throughout the Northwest Canterbury Plains are believed to be laterally extensive. They were deposited before the onset of Quaternary tectonic deformation in this area and so may offer an opportunity for large-scale magnetic reconnaissance surveying to delineate the underlying tectonic structure. It is expected that the magnetic susceptibility of these units would be detectable against the surrounding sedimentary magnetic signature.

It is not thought that the small sediment density contrast between the Quaternary Gravels and underlying Tertiary age sandstone and mudstone lithologies would offer a good target for gravity surveying, but it may be feasible to detect small scale variations in the depth to Torlesse basement. This should allow a large-scale tectonic structural model for this area to be defined.

12.4.4. Wells:

All deep (> 150 m) water wells in the area should be carefully logged by geoscientists as they may offer an important and invaluable scientific resource for the future. The small cost of having a trained professional log such wells (~1/50 of the drilling cost) appears to be minor compared to the data such wells offer. The recovery and analysis of borehole samples from important horizons should also be considered.

Part IV

Part IV

Results summary, synthesis, conclusions and future work

Outline of Part IV:

Part IV consists of three chapters. Chapter 13 summarises the results of Parts II and III of the thesis, covering the research results of the Omihi Valley study area, and the North Canterbury seismic reflection surveys at Burnt Hill, Racecourse Hill and Pines Beach. Chapter 14 is a synthesis of the widely distributed (temporally and geographically) research material from Parts I, II and III. Finally, Chapter 15, includes the overall conclusions of this research project and provides recommendations, based on these results, for future research and development. It also contains a brief synopsis of the research currently taking place, that is, as at the time of submission of this thesis.

Chapter 13. Summary of Results

To restate, the overall thesis aims are:

- *To undertake an integrated geological/geophysical survey utilizing detailed seismic reflection profiling of the Omihi Valley in order to develop a groundwater aquifer model and provide rational guidelines for future resource assessment and utilization for sustainable management.*

- *To conduct a pilot investigation, utilising modern seismic reflection equipment, across a selected major fault zone, in order to image its styles of deformation and temporal activity relationships, along the northwest margin of the Canterbury Plains, this in order to evaluate the effectiveness of the technique for future resource assessment; and*

- *To characterise, in several geographic areas, the major sedimentary units and in particular aquifer geometry of the north Canterbury Plains Quaternary sediments, and to assess their extent using geophysical techniques.*

13.1. Initial model:

It was initially predicted that seismic reflection surveys would delineate sedimentary architecture within the Late Quaternary sediments and associated faulting and folding of these sedimentary units, and it was anticipated that large-scale hydrological compartmentilisation, permeable pathways, and other hydrological architecture could be imaged, mapped and quantified. At the commencement of this study a simple hydrologic-geologic/tectonic model was proposed as being representative for the Northwestern Canterbury region aquifers. The model was based on personal communication with the water well drilling companies, limited geologic logs from Environment Canterbury's water wells database and analogous sedimentary basins (Martin, 1993).

My initial model envisaged a series of laterally extensive interfingering aquifers and aquitard horizons generally similar to those present in the subsurface below the Christchurch area as described by previous workers (Brown et al., 1995; Bal, 1996; Brown, 1998). This initial model inferred that the Northwestern Canterbury Plains aquitards consisted of clay/silt rich glacio-fluvial gravel sediments and, in areas progressively nearer to the coast the aquitards consisted of fines contents derived from progressively more marine environments eg. estuarine deposits, swamps, and marine inner shelf units. While aquifers were comprised of reworked, better sorted glacio-fluvial gravel sediments with little or no interstitial fines. This composite sedimentary architecture was further inferred to be locally complicated by ongoing active earth deformation, including folding and faulting. This initial model now appears to be too simplistic, and as a result of this study a recharacterisation for the aquifer/aquitard geometry is now proposed based on the results obtained in the Omihi Valley and North Canterbury high resolution seismic surveys and accompanying detailed well logging.

13.2. Results:

The key results obtained during the research are reviewed and summarised here in three sections, as follows: 1) Geophysical survey and borehole logging results applicable generally in the context of delineating subsurface geometry; 2) Omihi Valley seismic survey results; and 3) Burnt Hill - Racecourse Hill and Pines Beach seismic survey results.

13.2.1. General results:

1) It is shown that modern, shallow high resolution, P-wave seismic reflection surveying is capable of delineating sedimentary architecture in the Late Quaternary sediments of the North Canterbury Plains and rangefront valleys. Previous seismic reflection surveys have defined major lithologic units and structural geometry, but are generally inconclusive with respect to delineating sedimentary architectural detail (De Vel, 1984; Woodward, 1987). With the majority of groundwater resources being located below a depth of 50 m in north Canterbury (ECan, 2004), shallow seismic reflection surveying offers the only proven method for delineating and targeting groundwater resources.

2) Shallow high resolution, P-wave seismic reflection surveying can be applied successfully in at least eight geographically diverse locations in North Canterbury, using acquisition parameters that are tailored to the particular subsurface conditions. Seismic data quality

and penetration are dependent on near-surface conditions that are present in any given area (Finnemore and Pettinga, 2000; Roering et al., 2002).

3) The frequency content of the seismic reflection data is dependent on the physical parameters found at the location of each particular survey. Locations where the watertable is within 5 m of the surface and fine grained sediments are present, such as the Omihi Valley and Pines Beach, give reflection data with a useable reflection component up to 300 Hz. Assuming an interval velocity of 1600 m/s this gives a vertical resolution of ≈ 1.3 m (using ¼ wavelength criteria). Surveys undertaken over areas where more course grained sediments are found and where the watertable is at a greater depth, such as in the Racecourse Hill and Burnt Hill areas, results in a useable seismic reflection component of 120 Hz which, assuming an interval velocity of 1600 m/s, gives a vertical resolution of ≈ 3.3 m.

4) The P-wave seismic reflection method does indicate at least two limitations when applied in the Quaternary sediments of North Canterbury. Firstly, the delineation of variations in saturation in the subsurface is shown to be limited to imaging the watertable depth (using refraction component of the seismic wave-field). Secondly, interpretation of two-dimensional seismic reflection data is problematic without correlative data derived from other sources, such as borehole logs, outcrop geology, and other geophysical methods.

5) It is now inferred that the major control on aquifers/aquitard hydraulic properties in the Quaternary gravel dominated sediments of North Canterbury are changes in permeability not porosity, which in turn is controlled by the fines (clay/silt) content of the sediment matrix.

6) A simple hammer and plate survey is often as successful as the more labour-intensive source methods, providing good resolution and penetration. This means that surveys can be undertaken with minimal labour yielding comparable results to the more expensive and labour-intensive methods, such as mini-Sosie, explosives, and 12-gauge blank shotgun shells.

7) Extensive field experience has show that seismic reflection surveys are unlikely to be successful in wind velocities of greater than 20 knots or when raining. However, burying

the geophones increases usable seismic reflection frequencies and allows seismic surveys to be conducted in moderate to high winds (> 10 – 30 knots).

8) Several seismic reflection surveys on the North Canterbury Plains, shows that many 'advanced' processing algorithms usually applied to shallow seismic survey data tend to decrease the final stacked data quality, not increase it as is seen elsewhere. Deconvolution, for example is shown to be unsuccessful in increasing the useable frequency band and reducing reverberations. Residual statics appear to increase the coherency of reflection events, while refraction statics is found to give a poor improvement in data quality, and a simple velocity model for the near-surface usually produces more coherent stacked seismic sections. This may be the result of the very planar nature of the Canterbury Plains sedimentary units (Appendix 6).

9) Given optimum conditions, such as a well compacted, saturated road surface, over a well indurated/compacted sequence of limestone, sandstones and mudstones, shallow seismic reflection surveying with a simple hammer and plate seismic source is shown to produce survey penetrations which are comparable with more powerful seismic sources (explosives/mini-Sosie) (Appendix 6).

10) Seismic reflection surveying in unsaturated sediments can be successfully used for large scale delineation of gravel architecture. However, the data quality is poor in comparison to the more saturated areas (Appendix 2).

11) Screw-in geophones for use in gravel sediments increase the useable frequency content of the seismic reflection signal. However, the time involved in the "planting" of the screw-in geophone decreases the speed of the survey. The "time is money" adage likely means that the increase in frequency content obtained with the screw-in geophones does not outweigh the extra labour hours involved (Appendix 3).

12) Electrokinetic sounding (EKS) is not useful at delineating hydrologic/lithologic or stratigraphic detail within the Quaternary sediments of the Omihi Valley (Appendix 4).

13) Previous gravity surveys within the Omihi Valley only poorly define Quaternary and Tertiary structure. This is due to the small density contrasts between the Cenozoic lithologies present (Appendix 5).

14) The quality (both detail and accuracy) of well logging varies, but proper well logging is an important tool for subsurface geometry delineation. Drillers create logs which are highly variable in quality, ranging from the carefully described lithology and depth, to the "made up on the way home based on other wells in the area" approach. Careful logging requires specialist expertise, but an accurate log's value should not be underestimated (Appendix 7).

13.2.2. Omihi Valley results:

The Omihi Valley results are further subdivided into two sections. The first relates to the large scale sedimentary and tectonic structure of the valley, and the second, relates to the characterisation of the Late Quaternary valley fill sediments.

13.2.2.1. Sedimentary and Tectonic structure of the Omihi Valley:

The large scale structural delineation based on the seismic surveys and geologic mapping provides the following results:

1) The structural delineation of the subsurface in Omihi Valley to a depth of ~500 m, and the incorporation of the subsurface geology into a setting framework controlled by geologic mapping of the surrounding area, as well as the previously defined tectonic models for the North Canterbury region.

2) Several different seismic facies are delineated for the Cenozoic lithologies (Tertiary and Quaternary), which allow them to be constrained in the subsurface beneath the Omihi Valley.

3) Delineation of the Tertiary through to the early Quaternary formations within the Omihi Valley shows that they have a similar apparent dip. Based on this, it is believed that the onset of plate boundary related deformation commenced post deposition of the Kowai Formation (Lower Pleistocene, during the Upper Nukumaruan (1.1 - 1.5 myr) (Gregg, 1959; Browne and Field, 1985)).

4) Seismic reflection surveying shows that many of the topographic features in the Omihi Valley appear to have an underlying tectonic component (thrust faulting and thrust propagated folding), this is especially clear in the north of the valley.

5) The early Quaternary age Kowai Gravels do not contain aquifer units in their upper 10 metres beneath the Omihi Valley, and the gravels do not become "cleaner" with depth. The chance of locating aquifers throughout this area within the gravel member of the Kowai Formation is therefore reduced.

6) The extent of the Mt Brown Formation is mapped, and is identified as a possible aquifer containing unit and groundwater recharge path. Importantly, this means that the recharge area of the Omihi Valley is larger than was previously believed.

13.2.2.2. Characterisation of the Omihi Valley Late Quaternary sediments:

Within the Omihi Valley the following results have been obtained:

1) A map of the extent and volumes of the late Quaternary sediments where all major aquifers are presently located (except possibly well N34-139) in the Omihi Valley.
2) A detailed seismic facies model for the Late Quaternary sediments.
3) An interval velocity inversion is detected in the sediments which possibly correlate with a cleaner gravel aquifer unit.
4) Large-scale paleo-alluvial fan surfaces are delineated which can be seen to prograde out into the valley in the subsurface, and also what are inferred to be inter-fan erosional fluvial features (representing a possible future groundwater target for investigation).
5) The location of the Omihi Fault has been narrowed down to a zone on the southeastern Omihi Valley margin and lower foothill slope (possibly seen on seismic line Omihi-1S).
6) The post-Kowai Formation deformation in the Omihi Valley is imaged, and is represented by the synclinal warping of the Kowai Gravel reflector.
7) The delineation of on-going but reduced Late Quaternary deformation of the Omihi Valley sediments, as seen in warped Teviotdale and Canterbury gravel reflectors.

8) Evidence of ongoing deformation in the footwall of the Omihi Fault, in the southern part of the valley, is imaged in the seismic reflection surveys Omihi-1, Omihi-1S and possibly Omihi-3S (Figure 5.8 and 5.9).
9) The work of Loris (2000), based on water well drillers logs and limited geophysical surveys, indicated that the main producing horizons for the majority of the aquifers are contained in the Kowai Gravel member. With the newly obtained seismic reflection data and detailed well logs in this study, the stratigraphy is revised and groundwater resources are now interpreted to be almost completely confined to within the Teviotdale and Canterbury Gravels, forming the post-Kowai Gravel valley fill sequence.

13.2.3. North Canterbury results:

The seismic reflection surveys undertaken at Burnt Hill and Racecourse Hill indicate that the pre-Quaternary formations are highly deformed and complex in Northwest Canterbury. The deformation of the overlying Quaternary sediments is more difficult to delineate due the inherit complexity of the sedimentary architecture and the lack of logged boreholes to correlate with the sedimentary structure. The use of seismic reflection surveying is shown to image the Tertiary age lithologies below the Quaternary gravels, and intra-gravel architecture is also clearly imaged, but interpretation of those reflection images is limited by the lack of available borehole logs and detailed outcrop geological data.

The Pines Beach seismic reflection survey indicates that along the coastal North Canterbury Plains seismic reflection surveying can successfully delineate sedimentary detail down to sub-metre resolutions (for very near surface reflections a vertical resolution of ~1.6 m). The seismic surveying also shows that the sedimentary units are much more coherent and planar than seen elsewhere in inland north Canterbury.

Chapter 14. Synthesis

This chapter presents the synthesis of the results obtained from the geophysical and geological investigations in the three study areas. An improved understanding of the complexity of the aquifer/aquitard geometry from this research shows that the effect of small-scale active tectonic deformation is indecipherable against the sedimentalogical facies changes present in the subsurface.

14.1. Subsurface deformation vs surface rupture models:

At the commencement of this project the model of active fault deformation for the Canterbury Plains Quaternary gravels consisted of a fault plane propagating as a discrete planar structure upward through the gravels, progressively propagating to ultimately reach the surface, forming a fault scarp, and with the possibility that multiple fault strands may form in the near surface zone. Equally, as faults propagate into and through the Quaternary units a wider zone of fault-propagation folding is typically recognized, and this may be expressed at the surface by uplift, tilting and warping of depositional surfaces. This model is based on the previous research by participants in the Active Tectonics and Earthquake Hazard Research Programme, in the Department of Geological Sciences, University of Canterbury (e.g. (Cowan, 1992; Nicol and Wise, 1992; Al-Daghastani and Campbell, 1995; Litchfield, 1995; Armstrong, 2000; Pettinga et al., 2001; Roering et al., 2002; Campbell and Pettinga, 2003; Estrada, 2003).

Due to the seismic acquisition geometry used for the shallow seismic reflection surveys undertaken during this research (small maximum source-receiver offsets ~ 220 m), the imaging of steeply dipping structures, such as sub-vertical fault planes is unlikely to be successful, but displacement of lithologies across such faults should be imaged. In fact very little discrete displacement of lithologic units, associated with fault offsets is seen within the Late Quaternary gravels underlying locations where faults have previously been interpreted to rupture the surface. Minor lithologic discontinuities are seen in several surveys (Omihi-1, this study; Hawarden-1 (Roering et al., 2002)) but no large-scale fault plane dislocations are seen. Instead, within the Late Quaternary sediments in the 50-500 m depth range, initial deformation appears to be preferentially accommodated by near-surface folding and/or warping, with disseminated small displacements accommodating the deformation, and giving the overall appearance of ductile deformation accommodated by folding in the near surface. This deformation style has been imaged repeatedly in the Canterbury region over the last few years (e.g. across the Springbank fault – Estrada (2003) , Omihi-1 – this study; the Hawarden anticline – Roering et al. (2002)). Over time, as structures evolve, the reverse/thrust faults propagate to the surface, eventually forming the many well defined tectonically controlled fault scarps displacing Quaternary strata, and widely recognized throughout the Canterbury region. Some of these fault scarps have been trenched and revealed a pre-historic rupture record (e.g. (Sisson, 1999; Sisson et al., 2001)).

14.1.1. Aquifer geometry North Canterbury Plains:

The general sedimentary architecture of the Late Quaternary gravels beneath the Canterbury Plains is largely based on an extensive database of water well drilling logs, dating back to the 1860's (Brown et al., 1995). Researchers have delineated and mapped the large-scale formations within these gravels that constitute the main aquifer and aquitard horizons below Christchurch and elsewhere on the Canterbury Plains (Brown et al., 1995). However, limited recovery and mixing of sediments during the drilling process has meant that interpretation of small-scale sediment facies changes is not possible and geophysical borehole logging has proved unreliable in delineating facies-scale sediment changes (Bal, 1997). At present, it is not possible to directly recover an intact, representative sample of the differing sedimentary units present in the Canterbury Plains subsurface, so an approach such as modeling or sedimentary outcrop analysis is necessary. Recent field studies by Browne and Naish (2003) and modeling work by Moreton et al. (2002) has shown that the gravels of the Canterbury Plains are complex and show a large range of facies changes at many scales. Moreton et al. (2002) has used flume modeling based on similar sediment types present in the Canterbury Plains gravels and scaled down the geometry. The flume experiments result in a complex sedimentary model for the Canterbury Plains. If the scaling assumptions are correct, the model predicts that permeability distributions are complex with a range of permeability classes. Modeling and outcrop correlations indicate that the Late Quaternary Canterbury Gravels have the following properties:

1. High permeability pathways (aquifers) are secondary channel fills;
2. Low permeability zones (aquitards) are floodplain fines, erosional remnants, splays and fine-grained channels fills;
3. The bulk of the gravel consists of primary channel fills, with intermediate permeability.

Paleo-fluvial features on the Canterbury Plains are highly chaotic and laterally and vertically variable in scale. Paleo-fluvial features in the Omihi Valley are more continuous laterally with more variation vertically. This is the reverse of what would be expected for the two systems, as the Waimakariri River area is a major braided river system and the Omihi Valley catchment area is a series of meandering streams. On the seismic reflection scale it appears that the sedimentary facies generated by a high energy fluvial river is highly chaotic compared to meandering river styles.

14.1.2. North Canterbury Plains:

The seismic reflection and borehole data shows that the large-scale Quaternary sedimentary architecture beneath the North Canterbury Plains is more complex than that seen in the basin margin foothills valleys (such as Omihi) and the coastal areas. The lower energy, fluvial environment, of the foothills valleys appears to generate more laterally extensive condensed sedimentary facies. Whether this is the result of: i) the meandering fluvial style (more overbank deposits and avulsing rather than degradation channelling); ii). the difference in grainsize (more silt/clay sized sediments); or iii). the effect of alluvial fan material inter-fingering with the fluvial gravel sediment packages is not known. The more eastern sediments adjacent to the present coast, are characterised by a sequence of inter-fingered but laterally extensive aquifer and aquitard units. This sequence is interpreted to be gravels inter-fingering with finer-grained swamp, and estuarine to marine deposits. Work by Brown et al. (1995), Bal (1996; 1997) and Browne and Naish (2003) indicates that these sequences can be correlated to glacial eustatic sea-level changes during the last seven isotope stages (700,000 yrs). Initial work by the author indicates that this Late Quaternary sequence consists of highly repetitive thin (< 2 m) units, that appear from the seismic reflection surveys undertaken to be laterally extensive (Figure 10.8).

To the west from the coast the marine influence pinches out (e.g. (Browne and Naish, 2003)), and the seismic reflection surveys reveal Late Quaternary gravel units which become more discontinuous, disrupted and are of lower amplitude. This indicates that the subsurface architecture is more discontinuous and that seismic impedance contrasts are less. This change in reflection character is correlated with a change in the fluvial style as one moves from the estuarine/coastal environment in the east, to the increased braided river style in the central and western Canterbury Plains. Beneath the western Plains there appears to be a composite stack of cross-cutting, cut and fill deposits controlled by changes in climate, tectonic deformation and sedimentary processes throughout the Late Quaternary, while the eastern Plains are underlain by a repetitive sequence of estuarine/marine sediments with braided/meandering gravel sequences inter-fingering.

During glacial periods the western Canterbury Plains paleo-environment is inferred to have included a series of erosional valleys which, in response to an increased sediment supply from the upper catchment valley glaciation, rapidly filled with sediments. These degradational valleys are inferred to have been rapidly filled and overtopped by the glacial sediment flux, and the (now) unconfined braided rivers began depositing braid-plain material across the filled paleo-valley structures. In post-glacial periods the sediment flux reduced markedly, to the point where the rivers began eroding into the braidplain forming new degradational valleys, similar to those seen today in the western reaches of the Waimakariri River east of the foothills of the Southern Alps.

The general trends seen in the gravity data, shallow seismic reflection surveying data, the deeper industry seismic reflection data (which is deeper than the shallow seismic reflection data) and the outcrop geology indicate that the present western range front may continue below the Canterbury Plains, and that Burnt Hill and Racecourse Hill may represent the surface expression of a through-going, northeast-southwest trending, tectonic structure(s).

The cut and fill nature of the northwest Canterbury Plains Late Quaternary sedimentary history, along with active tectonic deformation along the northwest Canterbury range front provides an explanation for the highly variable depths/thicknesses encountered here for the Late Quaternary sediments.

Chapter 15. Conclusions and future work

15.1. Conclusions – Aquifer characterisation:

The Late Quaternary sediments of North Canterbury are formed in a range of depositional environments, including braided and meandering rivers, swamps and estuaries, shallow marine shelf, and alluvial fans. The sedimentary sequences derived from these marine, glacio-fluvial, fluvial and alluvial processes result in the generation of the important aquifer and aquitard units. A greater understanding of the porosity and permeability variations within these units is of key economic importance with respect to the groundwater resource. In north Canterbury the use of high resolution shallow, active source, P-wave, seismic reflection surveying is shown to be a valuable tool in the delineation of shallow-depth sedimentary structure. It has also been shown that shallow seismic reflection surveying is effective in delineating sedimentary facies architecture and associated hydrological units, when applied as part of an integrated approach using geologic outcrop mapping and borehole logging.

As part of this research it is shown that three different seismic reflection interpretation and acquisition methodologies can be used to characterise the location, distribution and geometry of aquifers within gravel lithologies. These three methodologies are:

1) *Seismic facies analysis:*
   A useful tool to determine the bulk lithology of the gravel units in the subsurface, allowing large-scale units that contain productive aquifers to be mapped and quantified. This method is not dependent on imaging individual aquifer units, but assumes that aquifers are likely to be present in similar sedimentary facies and those sedimentary facies have similar seismic facies. This appears to be the case in the Omihi Valley where aquifers are located in a zone between two major seismic facies, which correlate with two different lithological units (Teiviotdale and Canterbury Gravels).

2) *High resolution three-dimensional or pseudo three-dimensional seismic reflection surveys:*

This methodology can be applied to delineate individual sedimentary architectural units. The resolution required is dependent on the survey location and the sedimentary architectural structures which constitute the aquifer units. In the Omihi Valley, it appears that the aquifer units are paleo-channels of a similar size and geometry to the present streams draining the valley (5 m - 20 m in width). On the northwestern Canterbury Plains, the aquifer units appear to be larger in scale, with paleo-channels (possibly secondary channel-fill) located within cut-and-fill paleo-valleys.

3) *The mapping of seismic interval velocity changes:*
Initial results from a single well location (N34-139) indicate that seismic interval velocity inversion may be a useful way to delineate zones of more open framework gravels and sands within larger scale clay and/or silt bound sand and gravel units in the Omihi Valley. To fully test the correlation between interval velocity inversion and open framework gravels a larger statistical sample is needed. This methodology is dependent on high-fold seismic reflection data, with a good range of source-receiver offsets to allow the velocity changes to be accurately defined.. Currently the mechanism relating to the velocity decrease is not fully understood, but is inferred to be related primarily to changes in clay content. Due to the numerous sediment dependent variables that affect seismic P-wave velocity (grainsize, clast orientation, clast and matrix composition, water chemistry) the methodology is limited to sedimentary units where the general lithology is already well constrained and only deviations from that bulk character are being mapped.

The importance of accurate well logging and sampling is also highlighted and demonstrated in this study. In the Canterbury region many water wells have been, and continue to be drilled, however, proper well logging is generally NOT undertaken. Where wells are closely spaced, or the aquifers are well defined this is less important, but in water well frontier locations such as is the north Canterbury foothills valleys, and northwest Canterbury plains, this information is likely to be the only subsurface information available. Considering the high cost of well drilling it seems appropriate that a small percentage of this cost be used to accurately log and sample wells.

15.2. Conclusions - The effect of active tectonics on aquifer geometry:

The characterisation of active tectonic deformation on individual paleo-fluvial structures has proven to be impossible to achieve because the paleo-fluvial architecture is extremely complex, at a detailed scale; and also being laterally and vertically variable at several scales. This complexity can not be quantified in standard two-dimensional seismic sections, as the geometry of paleo-fluvial sedimentary facies consists of a series of complex, associated, multi-scalar, three dimensional, sedimentary units. Determining the effect active tectonic deformation would have on this complex architecture is unlikely to be possible in the near future, as an understanding of paleo-fluvial sedimentary architecture is necessary before its tectonic deformation can be adequately unravelled and quantified. The effect that large-scale active tectonic deformation has on the spatial distribution and geometry of aquifer-containing sedimentary units has been more successfully documented in this study.

15.2.1. Response of aquifers to tectonic controls – Omihi Valley:

It appears that active fault offsets have not directly affected the Omihi Valley Late Quaternary sedimentary infill (0- 200 m depth), but it has affected the depositional environment by influencing sediment supply. The uplift-driven stream incision has generated the erosional flux of sediments from both the southeast and northwest valley sides, and the structural uplift has further generated the depositional sediment (accommodation) space, as well as the warping of large-scale surfaces. Within the Omihi Valley it appears that the fluvial history (which is clearly closely linked to Quaternary active tectonic history) is the major control on aquifer formation, architecture and spatial distribution. Several tectonic controls on the subsurface hydrology of the Omihi valley have been identified, including:

- The formation of the Late Quaternary (post-Kowai Formation) broad synclinal (valley) depression (maximum depth 200 m), which contains the Canterbury Gravel and Teviotdale Gravel units which in themselves contain the majority of the producing aquifers within the valley.
- Ongoing, but reduced, deformation during the Late Quaternary which has resulted in the continuing generation of depositional space within the valley.
- Tectonically controlled uplift of the Omihi Valley margins which has resulted in erosion of the Omihi Valley margins, allowing alluvial fans to prograde into the valley. The development of these large alluvial fans appears from topographic and subsurface data to have directly influenced the distribution of sediment grain-size along the tectonically controlled southeastern and northwestern valley margins. It appears that sediment adjacent to these margins is flooded with fines (silt and clay

with consequent low permeability), resulting in clay bound gravels, clay and silt units, and so greatly reducing the likelihood of aquifer units being present.

- Many small-scale faults and folds are seen in the seismic sections within the Omihi Valley Quaternary infill and these are believed to have resulted in only minor alteration of groundwater pathways and partitioning of the aquifer/aquitard units.

15.2.2. Response of aquifers to tectonic controls – North Canterbury Plains:

Active tectonic controls appear to mainly affect the paleo-history of the braided river systems within the north Canterbury Plains. Tectonically-induced folding and warping has resulted in numerous active tectonic structures developing below the North Canterbury Plains, such as the Cust Anticline, Starvation Hill, Burnt Hill and Racecourse Hill. This has resulted in the over-printing of the composite braid plain model of the Plains with a complex history of river gradient alteration, diversion and changes in sediment load as these active structures have developed. Tectonic deformation has resulted in the uplift of Tertiary age formations at several locations close to the north Canterbury Plains margins, and has resulted in the pinching out of Late Quaternary sedimentary aquifers. Whether these Tertiary lithologies contain economic aquifers is not known, as drilling is normally terminated immediately upon these lithologies being reached. Only one well is known to be producing from the Tertiary in north Canterbury, and this is located near Waipara (Ecan well M34-5576).

Since the completion of field data acquisition for this thesis research project, further seismic reflection surveying has been undertaken in the Burnt Hill-Racecourse Hill area, as part of a collaborative project with ETH Zurich looking at fault geometry in an oblique plate convergent tectonic setting. Initial findings indicate that a similar highly-deformed and complex subsurface topography exists there. It appears that Tertiary stratal formations are dipping to the southeast at a similar apparent dip to that of the Burnt Hill structure. With Torlesse basement rocks outcropping at the Waimakariri Gorge and Tertiary age rocks seen at View Hill, it appears that a set of imbricate thrusts must underlie this area of the Canterbury Plains. It also appears that the paleo-Waimakariri River has had sufficient erosional power to maintain its general course during the ongoing deformation in the area, leaving only minor erosional remnants such as Burnt Hill, Racecourse Hill and possibly View Hill protruding through the Late Quaternary gravel deposits. During periods of aggradation, the paleo-topography has been swamped with sediment, progressively building to produce the present-day Canterbury Plains surface. It should be noted that the present Waimakariri River channel is a post-glacial, degradational feature over much of its length across the Canterbury Plains, which is believed to be incising into the slightly older post-glacial outwash surface.

15.2.3. Conclusions - Seismic reflection surveying on the Canterbury Plains and in the surrounding foothill valleys:

In this study shallow seismic reflection surveying was successfully applied on the Canterbury Plains utilizing a multitude of seismic sources and acquisition geometries. Nine geographical locations covering a total survey length of 6 km have been surveyed on the Canterbury Plains, with a further 17 km of surveying being completed in the Omihi Valley. Numerous other surveys located around North Canterbury have also been undertaken, but do not form part of this study. Only one survey at Racecourse Hill, showed no identifiable, laterally continuous reflectors, and this is attributed to the either the depth of the watertable (saturated layer) or the lack of discernable sedimentary facies architecture at this location.

The seismic penetration achieved has been variable, with penetrations of over 600 m achieved in the Omihi Valley and 400 m on the Canterbury Plains. Due to the low seismic velocity (350 m/s – 1200 m/s) of unsaturated gravels and refraction noise, it is necessary to use small source-receiver offsets, small receiver spacings and very careful muting of direct and refracted energy, to accurately image the very near surface (0 - 30 m) structure. These requirements reduce survey speed and so most surveys undertaken have a minimum interpretable depth of 30 m below the surface.

Migration of the seismic section is warranted and would probably allow small-scale sedimentary features to be more easily recognised. However, this was not possible during this thesis due to software processing requirements and also time limitations.

15.3. Future technological developments:

Seismic reflection surveying in North Canterbury undertaken for this thesis has used established, commercially available equipment where possible. The methods used and results achieved have been successful, but are limited by the rate of acquisition and its associated expense. The delineation of small-scale, active tectonic and hydrologic features, such as fault offsets, aquifer/aquitard units, requires multiple, parallel, two-dimensional lines or three-dimensional surveying techniques. The main controlling factor in acquisition rates is geophone placement and source operation. Automation of these would greatly increase the usefulness of seismic reflection surveying in North Canterbury, which in every other respect is geographically well suited to the wide application of the technique.

15.3.1. Pneumatic impact gun:

A small, pneumatically powered, seismic gun was developed and tested, and shows promise as a replacement for the hammer and plate source. It has a similar impact energy and repeat time, but can be fired tens of thousands of times per day (as opposed to several thousand for a hammer and plate). The present implementation requires the use of a petrol air compressor to charge the air supply tank every 36 impacts. This compressor is too noisy to be used at the same time as the source is fired, so for the source to be fully useable an electrical compressor or high capacity/pressure air vessel is necessary so the air tank can be recharged and allow near continuous surveying.

15.3.2. Towed array:

A new geophone placement method using a towed array, or land streamer has recently been developed by van der Veen et al. (2001). The method involves pulling an array of geophones and a source across the surface to be imaged. The relative source-receiver geometry remains constant, and by shooting at set intervals, a similar subsurface coverage to normal seismic reflection surveying can be obtained. An initial trial of a towed array system was undertaken at Pines Beach and appears to offer a rapid and useful method for data collection. The system developed for this pilot study differs from previous towed array systems of van der Veen et al. (2001) (in terms of its details in construction), the system trailed at Pines Beach is based on non-gimbaled 40 Hz geophone elements encased in a 5 kg concrete shell. This design allows an economically viable, mechanically robust, towed array to be constructed and easily maintained, and which is tailored for the flat gravel roads and fields of the Canterbury Plains. Initial surveying indicates acquisition rates of two to three times' conventional methods, but the method is limited by the use of manual sources such as the hammer and plate. Testing indicates that maximum acquisition rates for a towed array require an automated source system such as an accelerated weight drop or mini-vibrator.

15.4. Future research:

15.4.1. Additional geophysical methods:

The seismic reflection shot gather wave field contains a great deal more information than the P-wave reflection component. Within the wave field are shear wave reflection, ground roll, dispersive waves, and refraction information. P-wave reflection seismology uses only a small fraction of the available information. Multi-component acquisition (P- and S-wave) and processing methods, which use a larger component of the whole wave field, would allow a far greater amount of information to be derived about the subsurface (Pullan et al., 1990; Miller et al., 1993). P-wave seismic reflection methods have been shown to be successful at delineating sedimentary facies architecture in North Canterbury but the vertical and lateral resolution is limited by the inherit seismic absorption characteristics of the subsurface, which limit P-wave reflection wavelets to less than 300 Hz (average 120-200 Hz). The use of S-wave reflection methodology may allow higher lateral and vertical resolution due to the 4 - 6 times slower velocity of the S-wave in comparison to the P-wave. S-wave methods are also more sensitive to the saturation of the material that is being imaged (Pullan et al., 1990). Another possible useful method is Multi-Channel Analysis of Surface Waves (MASW).

Borehole logging using natural gamma-ray, gamma-gamma (density) and neutron logs has been shown to delineate lithostratigraphic units in the transgressive/regressive shoreline Quaternary deposits, located at Bexley, Christchurch (Bal, 1997). The detail seen in these logs appears to be quite high especially as the boreholes are steel-lined. A PVC-lined well would offer a better opportunity to determine lithology and may allow more detailed correlations between hydrologically important sediment changes and seismo-stratigraphic features to be delineated.

15.4.2. Extension the Omihi Valley case study to the Canterbury Plains area:

The research described in this thesis has shown that hydrologically important subsurface architecture on the Canterbury Plains and the Omihi Valley can be delineated using seismic reflection surveying. It has is also shown that lithologic variation in the Omihi Valley Late Quaternary gravels can be characterised, and a possible correlation drawn between low velocity layers within those gravels and "clean" gravel/sand aquifers. An important extension of this result would be determining if this low velocity inversion is present in the more laterally extensive Canterbury Plains gravels and if the lithology is such that the small velocity changes generated by pore space/clay content variability are greater than those generated by other sediment composition changes (grainsize/orientation/chemical composition). Any velocity inversion would also have to be shown to be greater than the inherent noise in velocity determination for seismic surveying controlled by near surface velocity variability, geometry accuracy, frequency content of seismic wavelet and lateral complexity of the subsurface architecture, including apparent dips of the subsurface lithology (Yilmaz and Doherty, 1987).

15.4.3. Reprocessing of the reflection data:

Processing of the seismic reflection data has been limited by the seismic processing software available. Comparisons with other processing software on similar data sets (Antarctic data) indicate that more advanced processing packages would allow an estimated 50% improvement in the coherency and clarity of the final stacked section. This is due to the lack of bent line processing algorithms, advance refraction static processing and other advanced processing routines in the current processing software. The careful reprocessing of the seismic data, with more advanced software would therefore result in a more detailed post-stack image and may allow smaller scale features to be interpreted.

15.4.4. Research plan:

A possible extension of this research would be the production of a set of pseudo-three-dimensional seismic lines adjacent to an accurately logged, producing well on the North Canterbury Plains. The well would need to be non-operational during the survey time, have discrete aquifer units at one or two defined depths between 30 - 150 m, and have been carefully logged (optimum would be cable-tool drilling) with full grainsize analysis of recovered borehole samples. The well should also be located in such a position that the underlying tectonic and structural context could be characterised. It is likely this would involve high resolution surveys along a large-scale deep structural seismic reflection line. A second series of three-dimensional surveys should be undertaken near to a second non-producing borehole (logged). The non-producing well would ideally be near the producing well to remove the effect of regional sediment changes. The seismic reflection acquisition would be tailored for careful true amplitude processing and to optimise the subsurface velocity model. To reduce the effect of the very near surface weathering layer velocity heterogeneities, surface-consistent refraction statics would be undertaken (Docherty, 1992).

To maximise the frequency content and hence vertical and lateral resolution the geophone and source would be placed below the unconsolidated surface layer. Accurate calibration of the two-way time could also be improved by undertaking vertical seismic profiles in the boreholes. The seismic data would then be carefully processed to determine if sedimentary architectural details were traceable in three dimensions beneath the Canterbury Plains where the sedimentary structures are likely to be larger than in the foothill valleys, such as Omihi Valley, bordering the Canterbury Plains[9]. With two data sets containing carefully logged borehole correlation data and full seismic data, the seismic attribute analysis which was undertaken in Omihi Valley could be repeated for the Canterbury Plains data set. It is expected that a similar velocity inversion will be detectable for the "cleaner" aquifer units. Once a simple correlation has been established, this would allow rapid seismic P-wave water exploration and characterisation to be undertaken on the Canterbury Plains.

15.4.5. Ongoing research:

Since the completion of the field research component of this thesis further seismic surveys have also been undertaken by the author at several other areas in North Canterbury. These include Hawarden, Waipara, Waimakariri Gorge (4 km), Cust (7 km) and Springbank (2 km). Initial seismic tests have been undertaken also by the author at West Melton and Kaitorete Spit. The seismic lines have produced successful seismic profiles in a diverse range of Canterbury Plains' environments and indicate that large-scale shallow seismic reflection surveying will greatly add to our understanding of the Plains sedimentary and tectonic history.

During the last stages of this thesis further field trials of the shallow, high resolution, paleo-fluvial identification methodology were undertaken in Omihi Valley. Two series of high resolution surveys (three parallel seismic lines, 392 m long, per survey) were carried out in the Omihi Valley. One was undertaken in the southern part of the Valley near where the structural delineation surveys had indicated up to 200 m of Late Quaternary sediments are present. The other was located in the north of the Valley where the Late Quaternary sediments are believed to be only 70 m thick and restricted to a 400 m zone adjacent to the eastern valley margin. In each survey location, several prospective paleo-channel features are seen on

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[9] Browne and Naish from outcrop data on the coast north of the Ashburton River mouth, have determined that the average thickness of the different gravel units is 0.3-2.5 m and < 30 m to 200 m wide {Browne, 2002 #15}. While Morton has determined using flume modelling that secondary channel fills are 0.5 m thick and 4 m wide (average of data).

several seismic sections indicating that the features are indeed laterally continuous (> 45 m along the valley axis). The paleo-features were then drilled, and initial findings indicate that the southern well intersected a strong producing aquifer (800 l/min) (per. comm. McMillan Drilling, 2004) at 80 m (within the error of the seismic method). The second well did not encounter a producing horizon at the depth of the paleo-channel-like feature, but did encounter a change from clay bound gravels to silty/clayey sediment. Initial interpretations of this borehole data are that the southern well intercepted a paleo-channel which contained clean gravels, while the north well is interpreted to have intercepted a channel feature which had been in-filled by much more fines-rich sediments from the eastern valley margin.

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Appendices

Appendix 1

Seismic sections and acquisition parameters for North Canterbury Seismic Surveys

Omihi Valley (large scale structural seismic surveys)

Omihi-1	(Sheet 1)
Omihi-1S	(Sheet 1)
Omihi-2	(Sheet 1)
Omihi-3	(Sheet 1)
Omihi-3S	(Sheet 1)
Omihi-3N	(Sheet 1)
Omihi-4A	(Sheet 2)
Omihi-4B	(Sheet 2)
Omihi-5	(Sheet 2)
Omihi-5S	(Sheet 2)
Omihi-6	(Sheet 3)
Omihi-7	(Sheet 3)
Omihi-8	(Sheet 3)
Omihi-9	(Sheet 3)

Omihi Valley Paleo-fluvial delineation seismic surveys

Omihi-UHR-1A	(Sheet 4)
Omihi-UHR-1B	(Sheet 5)
Omihi-UHR-1C	(Sheet 6)
Omihi-UHR-1D	(Sheet 7)
Omihi-UHR-1D-2	(Sheet 8)
Omihi-UHR-2A	(Sheet 9)
Omihi-UHR-2B	(Sheet 10)
Omihi-UHR-2C	(Sheet 11)
Omihi-UHR-2D	(Sheet 12)

Burnt Hill

Burnt Hill-1	(Sheet 13)
Burnt Hill-2	(Sheet 14)
Burnt Hill-3	(Sheet 15)

Racecourse Hill

Racecourse Hill-1	(Sheet 16)
Racecourse Hill-2	(Sheet 17)

Pines Beach

Pine Beach-1	(Sheet18)

Kingdom Suite project files are on CDROM 1- Box 1

Acquisition parameters for seismic reflection surveys

Acquisition Parameters for Omihi-1	
Source type	10 Kg hammer and plate
Source	Stacked shot (12 Stacks)
Source point minimum offset	0 m
Source point maximum offset	282 m
Shot points	129
Shot spacing	12 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 2 m spacing inline
Geophone group interval	6 m
Shooting spread	48 channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi-1S	
Source type	10 Kg hammer and plate
Source	Stacked shot (8 Stacks)
Source point minimum offset	0 m
Source point maximum offset	204 m
Shot points	24
Shot spacing	8 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1 m spacing inline
Geophone group interval	4 m
Shooting spread	48 channels (No roll through)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)

Acquisition Parameters for Omihi-2	
Source type	10 Kg hammer and plate
Source	Stacked shot (8 Stacks)
Source point minimum offset	0 m
Source point maximum offset	141m
Shot points	155
Shot spacing	3 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1m spacing inline
Geophone group interval	3 m
Shooting spread	48 channels (Push with no shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)

Acquisition Parameters of Omihi-3	
Source type	10 Kg hammer and plate
Source	Stacked shot (8 Stacks)
Source point minimum offset	24m
Source point maximum offset	282m
Shot points	129
Shot spacing	12 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 2 m spacing inline
Geophone group interval	6 m
Shooting spread	48 channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters of Omihi-3N	
Source type	10 Kg hammer and plate
Source array	Stacked shot (10 Stacks)
Source point minimum offset	0m
Source point maximum offset	200m
Shot points	21
Shot spacing	12 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 2m spacing inline
Geophone group interval	6m
Shooting spread	42 channels (constant spread, no roll on)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters of Omihi-3S	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 Stacks)
Source point minimum offset	0m
Source point maximum offset	235m
Shot points	68
Shot spacing	10 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1.6m spacing inline
Geophone group interval	5 m
Shooting spread	48 channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi-4A	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 Stacks)
Source point minimum offset	0 m
Source point maximum offset	306 m
Shot points	102
Shot spacing	12 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 2m spacing inline
Geophone group interval	6 m
Shooting spread	48 channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi-4B	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 Stacks)
Source point minimum offset	0 m
Source point maximum offset	306 m
Shot points	105
Shot spacing	12 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 2m spacing inline
Geophone group interval	6 m
Shooting spread	48 channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi-5	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 Stacks)
Source point minimum offset	0 m
Source point maximum offset	306 m
Shot points	170
Shot spacing	12 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 2m spacing inline
Geophone group interval	6 m
Shooting spread	48 channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi-5S	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 Stacks)
Source point minimum offset	0 m
Source point maximum offset	306 m
Shot points	41
Shot spacing	12 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 2m spacing inline
Geophone group interval	6 m
Shooting spread	48 channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi-6	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 Stacks)
Source point minimum offset	0 m
Source point maximum offset	260 m
Shot points	116
Shot spacing	10 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1.6m spacing inline
Geophone group interval	5 m
Shooting spread	48 channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi-7	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 Stacks)
Source point minimum offset	0 m
Source point maximum offset	260 m
Shot points	288
Shot spacing	10 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1.6 m spacing inline
Geophone group interval	5 m
Shooting spread	48 channels (Push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi-8	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 Stacks)
Source point minimum offset	30 m
Source point maximum offset	212 m
Shot points	78
Shot spacing	4 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1m spacing inline
Geophone group interval	2 m
Shooting spread	48 Chan.(Push with shoot through at both ends)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi -9	
Source type	10 Kg hammer and plate
Source array	Stacked shot (6 Stacks)
Source point minimum offset	0 m
Source point maximum offset	188 m
Shot points	60
Shot spacing	8 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1.3 m spacing inline
Geophone group interval	4 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi –UHR-1A	
Source type	10 Kg hammer and plate
Source array	Stacked shot (1 Stack)
Source point minimum offset	0 m
Source point maximum offset	188 m
Shot points	192
Shot spacing	2 m spacing
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, grouped
Geophone group interval	2 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi –UHR-1B	
Source type	10 Kg hammer and plate
Source array	Stacked shot (1 Stack)
Source point minimum offset	0 m
Source point maximum offset	188 m
Shot points	192
Shot spacing	2 m spacing
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, grouped
Geophone group interval	2 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi –UHR-1C	
Source type	10 Kg hammer and plate
Source array	Stacked shot (1 Stack)
Source point minimum offset	0 m
Source point maximum offset	188 m
Shot points	192
Shot spacing	2 m spacing
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, grouped
Geophone group interval	2 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi –UHR-1D	
Source type	10 Kg hammer and plate
Source array	Stacked shot (6 Stacks) 4m spacing
Source point minimum offset	0m
Source point maximum offset	188m
Shot points	60
Shot spacing	N/A
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1.3m spacing inline
Geophone group interval	4m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi –UHR-1D-2	
Source type	Seismic gun, 12 gauge blank
Source array	Single shot
Source point minimum offset	0 m
Source point maximum offset	188 m
Shot points	60
Shot spacing	N/A
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1.3m spacing inline
Geophone group interval	4m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi –UHR-2A	
Source type	Seismic gun (single 12 gauge blank)
Source array	N/A
Source point minimum offset	0 m
Source point maximum offset	188 m
Shot points	190
Shot spacing	2 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, grouped
Geophone group interval	2 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi –UHR-2B	
Source type	Seismic gun (single 12 gauge blank)
Source array	N/A
Source point minimum offset	0 m
Source point maximum offset	188 m
Shot points	190
Shot spacing	2 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, grouped
Geophone group interval	2 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi –UHR-2C	
Source type	Seismic gun (single 12 gauge blank)
Source array	N/A
Source point minimum offset	0 m
Source point maximum offset	188 m
Shot points	190
Shot spacing	2 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, grouped
Geophone group interval	2 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Omihi –UHR-2D	
Source type	Seismic gun (single 12 gauge blank)
Source array	N/A
Source point minimum offset	0 m
Source point maximum offset	188 m
Shot points	190
Shot spacing	2 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, grouped
Geophone group interval	2 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Burnt Hill-1	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 - 12 Stacks)
Source point minimum offset	0 m
Source point maximum offset	260 m
Shot points	133
Shot spacing	10 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1.5 m spacing inline
Geophone group interval	5 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Burnt Hill-2	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 - 12 Stacks)
Source point minimum offset	0 m
Source point maximum offset	260 m
Shot points	168
Shot spacing	10 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1.5 m spacing inline
Geophone group interval	5 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Burnt Hill-3	
Source type	10 Kg hammer and plate
Source array	Stacked shot (6 Stacks) 4m spacing
Source point minimum offset	0 m
Source point maximum offset	188 m
Shot points	53
Shot spacing	8 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1.3 m spacing inline
Geophone group interval	4 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Racecourse Hill-1	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 Stacks)
Source point minimum offset	0 m
Source point maximum offset	260 m
Shot points	98
Shot spacing	10 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1.3m spacing inline
Geophone group interval	5 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Racecourse Hill-2	
Source type	10 Kg hammer and plate
Source array	Stacked shot (8 - 16 Stacks)
Source point minimum offset	0 m
Source point maximum offset	260 m
Shot points	241
Shot spacing	10 m
Geophone type	30 Hz Mark Products
Geophone array	3 series geophones, 1.6 m spacing inline
Geophone group interval	5 m
Shooting spread	48 channels (push with shoot through at end)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Acquisition Parameters for Pines Beach-1	
Source type	10 Kg hammer and plate
Source array	Stacked shot (4 Stacks)
Source point minimum offset	2 m
Source point maximum offset	48 m
Shot points	63
Shot spacing	4 m
Geophone type	40 Hz Mark Products
Geophone array	Single geophone
Geophone group interval	2 m
Shooting spread	24 channels (towed array, constant 24 channels)
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25 ms (4000Hz)
Trace length	1 s (4000 samples)

Appendix 2

Seismic reflection surveying in non-saturated glacio-fluvial gravel deposits, Rakaia River Gorge, inland Canterbury

Summary:

The aim of this survey is to evaluate if P-wave seismic reflection surveying can detect the various sedimentary units present within gravels of glacio-fluvial origin in the Rakaia River Gorge, inland Canterbury, at a location where the units are exposed in an adjacent outcrop. This would allow a direct correlation between seismic and geologic stratigraphy. The seismic survey was successful in delineating the basal contact of the outwash gravel with underlying lacustrine silt, and also provided limited structural detail within the thick (90 m) gravel unit. The dominant frequency of the reflections was 75-140 Hz giving a vertical resolution of 5 m and a horizontal resolution of 20 m. The glacio-fluvial gravels appear to be unsaturated throughout, with a perched water table above the gravel/silt transition at 120m below the ground surface. The depth of penetration with the hammer source and the receiver geometry used was greater than 150 m. The first 40 m is dominated by refraction energy which masks the very near surface reflections and could not be removed with processing. This survey demonstrated that seismic reflection is capable of imaging paleo glacio-fluvial structures in Torlesse derived gravels from 40 m to greater than 150 m. It is expected that in an environment where the gravels have a higher near-surface water saturation, the propagation of seismic energy into the ground would be enhanced (Steeples and Miller, 1991). This should improve penetration of the seismic energy and possibly increase the high frequency content, improving lateral and vertical resolution.

Introduction:

This appendix describes a shallow P-wave seismic reflection survey undertaken to evaluate its effectiveness in a non-saturated glacio-fluvial deposit to image inter- and intra-gravel reflections. An important factor in the survey is that the seismic reflection profile can be directly correlated with the glacio-fluvial depositional structure, as the seismic line was undertaken adjacent to a vertical cliff formed by rapid (post glacial) river down-cutting through the glacio-fluvial aggradational gravel deposits. The cliff's vertical face is 160 m high and divided into a lower unit of varved silt deposits of lacustrine origin and an upper unit of glacio-fluvial Torlesse greywacke derived gravels. The gravels are inferred to be unsaturated as no seepage can be seen from the inter-gravel interfaces, but seepage is seen at the gravel/silt interface. This is what would be expected with the saturated zone forming a convex upward surface from the river tending towards asymptotic with the present day surface, as the distance from the river increases. It can be inferred that the gravel deposits contain some water from vertical percolation from the surface, but this flow would not be expected to reach fully saturated equilibrium.

The transmission of P-wave seismic energy is dependent on many parameters including lithology, orientation of sediment clasts, void space and degree of void saturation by water. The aim of this survey is to evaluate which parameters within the gravel unit generate a seismic reflector and whether these can be correlated with a photographic log of the cliff section.

Geological Setting:

The Rakaia Valley has many glacial features evident throughout its length. At the head of the valley are several remnant glaciers, including the Ramsey, and along its length are moraine features and multi-level terraces indicating repeat glacial cycles (Soons and Gullentops, 1973) (Figure A2.2). The present Rakaia River occupies a braided river channel 160 m below the aggradational surface formed by the late Pleistocene cycles of glacial advance and retreat. The terrace selected for this seismic experiment is mapped as the Bayfield II Advance (15 - 27 kyr) and has Bayfield II moraines on its top (15 kyr) (Soons and Gullentops, 1973; Wilson, 1989). Underlying this aggradational terrace and deposit are yellow/grey silt and gravel with a highly disrupted and folded fabric, which is interpreted to represent a pro-glacial or ice marginal lake deposit from an earlier glacial cycle. Evidence for the formation of glacial lakes during the late Pleistocene glaciation are visible throughout the Rakaia Gorge and are common today in New Zealand at several locations where glacial retreat has occurred such as Punikiki and Mt Cook (Gage and Suggate, 1958). Where a retreat is followed by an advance distortion and disruption of lake sediments may also occur. The top surface of the lake sediments at the study site appears to be an erosional surface but this has not been dated. Whether the two units represent a continuous sedimentary succession, or alternatively there is a disconformity between them is unknown. At the end of the late Pleistocene glacial episode

(~ 14,000 kyr), the Rakaia River rapidly cut down into the aggradation surface to achieve a stream profile in equilibrium with base level. The last Acheron glaciation has a mapped aggradational surface as high as the Bayfield II Advance on the western side of the Rakaia River. This indicates that the present gorge is likely to have formed after the glaciation and therefore may represent a geomorphic feature which has repeatedly formed after each glacial advance and retreat. The Rakaia River has cut through over 180 m of sediment since the end of the last glaciation giving a downcut rate of 1.1 cm per year. This rapid down-cutting has resulted in a narrow (<1.5 km) wide, meander path being formed, with near vertical sides. The north and south terraces are at the same height (+/-10 m) and similar sedimentary sequences are present. The underlying silt unit is believed to have been deposited in a lacustrine glacial environment. This environment could have been present during the last glacial cycle and may indicate that at the survey location a large, pro-glacial lake existed. This pro-glacial lake would have been a long-term feature as the sediments are over 30 m thick and contain very fine varve layers that may represent cyclic annual or bi-annual sediment flux changes. Clean, un-weathered, course angular gravels, unconformably overlie the varve silts. The presence of this gravel indicates the glacial lacustrine environment was followed by a rapid influx of new clastic sediment. This is likely to have occurred at the end of the glacial cycle as sediment stored in the glacial moraines and glacial bed load became available for fluvial transport and was re-deposited further down valley.

Survey objectives:

The main objectives of this survey are:

- to evaluate if a shallow, p-wave, seismic reflection survey can detect the subtle lithologic and depositional layering present within gravel units of glacio-fluvial origin; and
- to detect the basal reflector of the gravels and the water table reflector if present.

The gravel clasts are of Torlesse greywacke origin and were derived from the Rakaia River catchment, one of the major sediment sources for the Central Canterbury Plains. The material at the survey location should therefore be representative of the material present below the main part of the Canterbury Plains. If lithologic and depositional changes can be detected in the unsaturated gravels at this location then it may be possible to delineate the inter-gravel unit below the Canterbury Plains also.

Survey Site:

The seismic survey was undertaken in the Rakaia Gorge on Bayfields Farm, 7 km northwest of the Rakaia Gorge Bridge (Figure A2.1). The Rakaia River has incised into the gravel deposits and the location offers a 160 m near vertical gravel cliff face, with a flat top and safe access.

Method:

The seismic reflection profile was undertaken on 14th December 2000. The seismic line was acquired using the acquisition parameters outlined in Table A2.1.

Geometry	Distances (m)
Nearest offset	20
Farthest offset	114
Receiver spacing	2
Shot spacing	2

Seismograph	Geometrics StrataVisor
A/D	24 Bit
Acquisition filters	None
Sampling	Interval
Record Length	1s

Source	Parameters
Type	Hammer (10kg) and Plate
Stacks	8
Total Shots	96

Geophone	Parameters
Element Type	30 Hz (0.65 damping)
Geophone String	Three phones bunched
Surface/Buried	Buried 5 cm

Notes	Geometry constant, no shoot through at at the end of line

Table A2.1: Acquisition parameters for the Rakaia Valley seismic survey.

The weather conditions were very windy (>30 knots), so the geophones were buried as far as possible (given the difficult gravelly terrain, this was generally 5-10 cm deep). The shot and receiver locations were measured using a measuring tape and topography varied by < 0.2 m along the line, therefore no elevation data were recorded.

Processing :

The raw seismic data were processed using standard seismic processing parameters (Yilmaz and Doherty, 1987). Care was taken to identify and remove sources of noise, both environmental and source-induced, so that the final seismic section contained only true reflection data. Careful filtering was applied in the shot domain to maximise the frequency content of the data and minimise noise. The processing procedure adopted is presented in Table A2.2.

Processing Flow Diagram
Convert from SEG-2 to SU Format
⇩
Resample to 500 samples at 0.5 ms sampling rate
⇩
Apply geometry
⇩
Remove bad traces
⇩
Frequency filter (Band pass) 80-120-200-300 Hz
⇩
AGC gain 50ms window
⇩
Mute shot noise cone -140m , 0m, +140m
⇩
Sort into shot gathers
⇩
Velocity analysis using constant velocity stacks, semblance
NMO correction using 1000m/s
⇩
Stack
⇩
AGC Gain 50 ms window
⇩
Trace addition using 0.5,1,0.5 filter

Table A2.2: Seismic processing flow for the Rakaia Valley seismic survey.

Ground roll and air blast were removed using a shot noise cone mute. Refraction energy was not muted but was analysed to evaluate where it stacked in the final stacked section (Steeples and Miller, 1998). Analysis indicated that all refraction and trapped wave energy stacks in the top 100 ms TWT ($\approx$ 40 m) of the final stacked section with normal moveout velocities (NMO) of <800 m/s. This part of the final section should therefore be ignored when interpreting.

Survey Results:

The high winds reduced the signal to noise ratio (S/N) on the raw shot gathers dramatically. The 8-fold stack improved the S/N ratio, but time and field assistant limitations meant that further stacking was not possible. It is likely that further stacking would have further reduced wind effects. Overall the raw shot gathers indicate that the survey was of poor quality. The shot gathers show a strong trapped wave and refraction signal which swamps the near surface signal (<40 m) complicating processing and interpretation. The raw shot gathers show some hyperbolic reflection events are present, but have a small NMO velocity indicating low (<1300m/s) interval velocities are present. This is due to P-wave seismic velocities being low in unconsolidated material which has not reached full saturation (Domenico, 1974). The large depth from the surface to the water table seems to have generated trapped wave energy. Figure A2.3 shows the cliff face below where the seismic line was undertaken and below it the final stacked seismic section. The photograph is taken looking southeast from the western side of the Rakaia Gorge.

Interpretation:

The final unmigrated seismic section can be divided into several different seismic facies:

Seismic Facies A:

Facies A is interpreted to be the seismic refraction energy that has been stacked into the final section due to poor muting of the refraction and trapped wave energy. The apparent features within this unit are believed to be caused by heterogeneity in the very near surface material causing lateral velocity changes. The refractions wave paths vary due to this heterogeneity. The refraction energy is then stacked using the reflection CMP geometry causing constructive and destructive interference effects. This causes the appearance of reflectors fading in and out and also steeply dipping reflection-like artifacts. At a depth of 40m, a near horizontal event is present. This may be a reflection but can not be definitely separated.

Seismic Facies B:

Facies B is dominated by more laterally continuous horizontal to sub-horizontal reflectors. Three major high amplitude reflection events are present and these are interpreted as intra-gravel reflection packages.

Seismic Facies C:

Facies C has much lower amplitude, discontinuous reflectors with only one major reflection event present. This is interpreted to be the basal gravel/silt horizon and may represent a local zone of saturation, above the less permeable varved silt unit. In outcrop, this zone was seen to be saturated and had water seeping from just above this unit.

Conclusions:

The seismic survey successfully delineated the gross stratigraphy and appears to have delineated several reflector packages within the main gravel unit. Correlating these packages with packages seen in outcrop proved difficult because of the strong heterogeneity seen within the gravel. A highly variable mixture of paleo-fluvial units can be seen within the gravel. The individual units that constitute the smallest scale paleo-flow depositional features are not continuous but rapidly pinch-out laterally. The seismic reflection profile demonstrates that shallow seismic reflection is capable of imaging sediment changes between clean gravel and varve silt and also demonstrates that intra-gravel depositional changes within the aggradation gravel can be delineated. The direct correlation between individual sediment packages in the gravel and the seismic reflectors is difficult due to the inherent three-dimensional nature of the fluvial deposits and the two dimensional nature of the seismic line. The seismic line was offset from the cliff face by 50 m for safety reasons and to reduce surface effects caused by the sediment/air interface at the cliff face. The seismic reflection profile shows sub 5 m vertical resolution features and what appear to be smaller scale horizontally continuous features. The general large-scale features in the image match the seismic expression.
Analysis of the raw and stacked data indicates that several survey acquisition parameters were poorly chosen to meet the aims of the survey. The 12-fold nature of the survey made semblance velocity analysis impossible and so a constant velocity stack was used to derive stacking velocities and hence interval velocities. At least 24-fold data is likely to be necessary (with a range of offsets) for the use of semblance velocity analysis.

Wind has a dramatic effect on the acquisition of the seismic data. Even in an area with no vegetation where the geophones are buried, wind causes vibration of the geophones that will swamp any reflection signal. Seismic acquisition was possible in 20-knot winds with eight stacked shots and buried geophones but was far from optimum. At the survey location, strong catabatic or anabatic winds are present at nearly all times of the day and so rescheduling of the survey was not practical. The large depth to the vadose zone causes the generation of trapped wave energy which masks near surface reflections.

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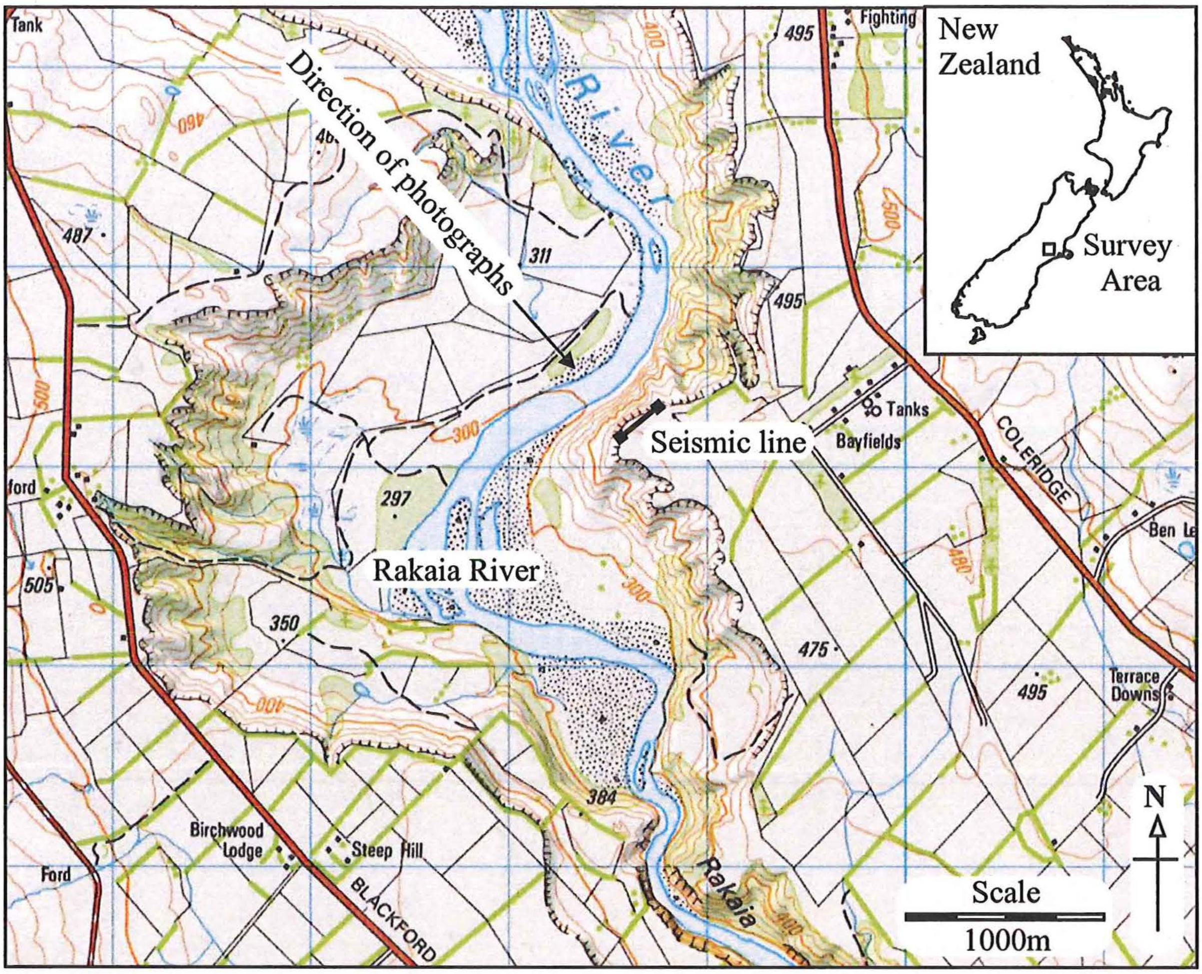

Figure A2.1: Location of the Rakaia River Gorge seismic survey and direction of photographs taken of cliff face.

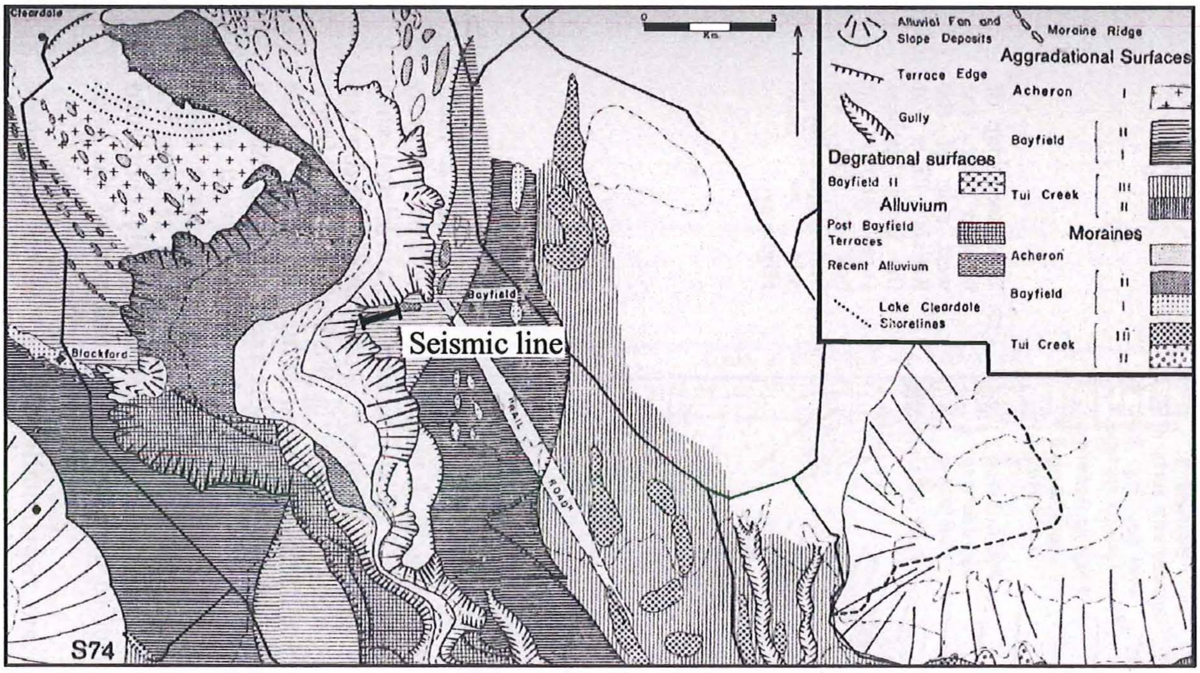

Figure A2.2: Geomorphological map of the Rakaia Gorge showing extent and age of the terraces and moraines. (adapted from Soons and Gullentops, 1973)

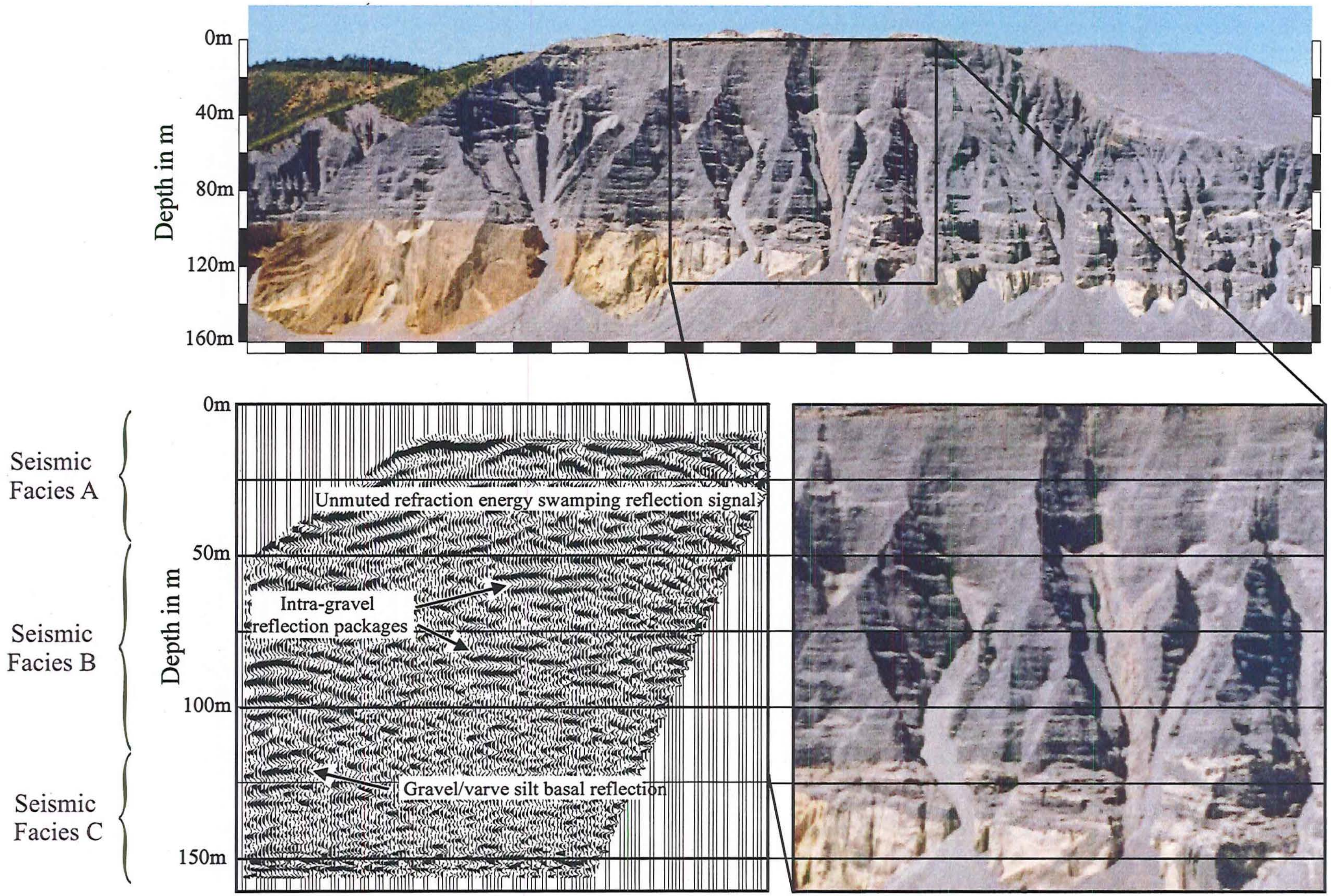

Figure A2.3:
A: Photograph of cliff face with large scale a sedimentary fabric features
B: Seismic section with seismic facies and equivalent part of cliff face.

Appendix 3

Field evaluation of a novel screw-in geophone

Summary:

This appendix describes the development of a new screw-in geophone. The aim of the new geophone is to increase the usable high frequency bandwidth of the receiving component of a seismic reflection system. Any increase in high frequency content of seismic reflection data increases the resolution in the final stacked section and may allow smaller features to be imaged (Yilmaz and Doherty, 1987; Sheriff and Geldart, 1995). Preliminary results indicate that the screw-in geophone successfully increased the higher frequency content of the received signal, but the extra effort required to plant the geophones was unwarranted in the North Canterbury region where they were tested. Similar results could be obtained by using a mechanical auger to rapidly drill a 8" (20cm) diameter, 0.5 m deep hole and manually plant the geophones directly, into more consolidated or saturated material.

Introduction:

The lateral and vertical resolution of P-wave, shallow seismic reflection surveying is controlled largely by the maximum frequency of the seismic wavelets that can be transmitted through the subsurface and recorded (Widess, 1973). The response of the seismic recording system and the earth can be represented by the convolution of the seismic source wavelet, the earth's response and the receiver response:

*Source (1) * Earth Response (2)* Receiver (3) = Final response*

(1) Source

Extensive field tests were undertaken to maximise the source input frequency band. Several seismic sources were tested with a variety of coupling parameters and operational methods. These included:

- Hammer and plate

Various hammer and plate weights were used as well as the number of stacks, and the depth of hole for the plate.

- Mini-sosie (Earth rammer)

The mini-sosie source was operated on compacted and uncompacted material. The length of ramming segment and number of earth rammers were varied.

- Seismic gun (12 gauge, blank, shell pipe gun)

The blank charge size and packing was altered as were the depth and saturation of the hole.

The hammer and plate source was chosen as the source for further testing as it was simple to use and gave a high frequency source wavelet.

(2) Earth Response

The earth's response is determined by local geologic and near-surface conditions. The only potential user-controlled subsurface parameter for a survey, is the near-surface water saturation. This can be controlled by delaying the survey until the subsurface has become saturated after a period of rain. The transmission of P-wave seismic energy is dependent on the water saturation of unconsolidated material and higher saturation increases the transmission of seismic energy and the bandwidth (Baker et al., 1997). Once the optimum source and environmental conditions have been selected or occurred, the only other parameter that is user selectable is the receiving elements response.

(3) Receiver

The response of the receiving element (geophone) is controlled by the physical characteristics of the geophone element and also the coupling of the element to the subsurface. Work by Washburn, Hover, Krohn and Tan and Drijkoningen has established that ground coupled geophones can be modelled as a system of two damped springs and masses (Figure A3.1) (Washburn and Wiley, 1941; Hoover and O'Brien, 1980; Krohn, 1985; Tan, 1987; Drijkoningen, 2000). Using this model the system has two resonant frequencies: The natural resonant frequency of the geophone element and the resonant frequency of the ground coupled geophone. The damping of the geophone element is dependent on the construction characteristics of the element and the electrical damping applied, while the ground-coupled, geophone damping is a function of the ground-geophone contact and the subsurface characteristics.

A plot of modelled amplitude response shows a rapid increase of sensitivity in the ground coupled geophone at the natural frequency of the geophone and a second larger peak at the geophone-ground coupling resonant frequency (Figure A3.1). It indicates that with low ground geophone damping and poor coupling, the ground coupled geophone acts as a low pass filter. It has strong ringing at the ground coupled resonant frequency and a phase change at higher frequencies (Figure A3.1). With high dampening (due to good coupling) the coupling resonance has a low peak and flatter amplitude response and a phase change at a lower frequency than the lower damped ground coupled geophone (Figure A3.1).

Key findings of the ground coupled geophone response:

High frequency data requires good coupling to achieve transmission of the signal, but also to reduce the effect of coupling resonance, which can cause ringing and phase distortion at the resonant frequency. Drijkoningen (2000) indicates that there are only two forms of coupling: Weight-coupling and spike-shear coupling. Spike-shear coupling according to Drijkoningen is "good" coupling, while weight coupling is "bad". A screw-in geophone will allow the geophone element to be strongly shear-coupled to the subsurface while the extra mass will increase any weight-coupled component.

The primary response of a geophone is its intrinsic frequency response. Geophones are designed to have an optimum response around a set, natural frequency. However the actual response of the geophone is not only at this natural frequency, but also throughout a band, which is usually taken to be one decade above and one decade below this natural frequency (e.g. a 30 Hz geophone has a reasonable response to seismic energy between 3-300 Hz) (Steeples and Miller, 1991). This response band allows a range of surveying to be accomplished in differing subsurface conditions without the necessity of having many sets of geophones with different characteristic responses. The secondary controlling factor for geophones frequency response is coupling with the subsurface. The density and shear modulus of a material determine the material's ability to transmit high frequency seismic energy. The very near surface material (0-30 cm), which is usually unconsolidated and unsaturated, rapidly attenuates high frequencies. To reduce this effect it is common to place long spikes on the geophones so that a preferential path is established through the very near surface material, directly into the base of the geophone. This method is robust and relatively quick but has two limitations: One, the spike must be as long as the unconsolidated material is deep. If the unconsolidated material is unusually deep, the spiked geophones become difficult to handle and insert. Two, the geophone itself is often left above the surface and is therefore strongly affected by wind and rain. To mitigate these limitations a new screw-in geophone was designed and tested.

Screw-in geophone design criteria:

The geophone design must meet several important criteria to be useful for field operation:

1. The unit must be robust:

   The geophone must be able to penetrate the weakly consolidated very near-surface material, but also must penetrate some of the underlying consolidated material so that good coupling to the subsurface is achieved. In the North Canterbury area, this consolidated material is composed of gravels with a clay matrix. The geophone casing must therefore be constructed of steel if it is to have an economically useful life.

2. The unit must be easy to plant and remove:

   A large percentage of time involved in any seismic survey is taken up with planting and removing of geophones (>30%). Any increase of total survey time increases the expense of the surveying and so must be minimised. The screw-in geophone was therefore designed to be mechanically inserted and removed by a powered unit.

3. The unit must be cost-effective:

   As a large number of geophones are required for any survey, the individual cost of each unit must be low enough so that the overall cost of the equipment and therefore any survey can be kept to a reasonable level.

4. The response must be as neutral as possible:

   The screw-in geophone must have a response that does not affect the seismic signal in such a way that the processing of the signal is invalid. The phase response should be as near zero as possible and have few spurious frequencies.

Final screw-in geophone design:

The screw-in geophone design uses a solid piece of steel that has been machined to form a tapered cone. Over this cone, a single steel rod has been bent and attached to produce a very course thread. The bottom of the thread has been sharpened to produce a cutting edge, allowing the unit to cut into the ground as it is turned. A large diameter hole has been machined into the top of the cone to accommodate a single geophone element. The element is glued into place using a very thin layer of silicone rubber at the base of the hole. A hole has been drilled in the side of the steel cone through which the signal cable is inserted. The top of the steel cone has been machined to form a hexagonal head over which a large diameter wretch driver fits. A small groove has also been milled in the wretch driver through which the signal cable is able to fit. The cable is then attached onto the wretch driver using a small clip.

The design is relatively easy to build and robust. The final design for the screw-in geophone is shown in Figure A3.2.

Screw –in geophone test:

To evaluate if the screw-in geophone design would increase the high frequency content of reflection data the new geophone design was field-tested in June 2000. Due to time limitations a simple walkaway seismic reflection test was used to evaluate the effectiveness of the geophones. Acquisition parameters are shown in Table A3.1. An initial comparison setup was planted using standard 30 Hz undamped 3" spiked geophones. The spread consisted of 48 channels with three geophones closely grouped at each receiver location. Shots were then recorded at offsets of -92 m, 0 m, and 92m from the first geophone group. The experiment was then repeated with geophones 46, 47 and 48 replaced with screw-in geophones. The test was not a direct comparison, because the screw-in geophones consist of single, 30 Hz elements while the normally planted geophones consisted of a string of three geophones connected in series and bunched.

Acquisition Parameters for Screw-in geophone test	
Name of survey	Omihi SG test 1
Source type	10 Kg Hammer and plate
Source array	Stacked shot (4 Stacks)
Source point location	0m
Shot points	1
Source duration	N/A
Geophone type	30 Hz Mark Products undamped and screw-in geophones
Geophone array	3 series geophones, point grouping (20cm)
Geophone group interval	2m
Shooting spread	48 Channels off end
Field filters	None
Recording system	Geometric 48 Channel Stratavisor NX
Sampling Rate	0.25ms (4000Hz)
Trace length	2s (8000 samples)

Table A3.1: Acquisition parameters for screw-in geophone test.

Site details:

The survey was located in Northern Canterbury, several hundred metres to the north of Omihi Hall, north of the main North-South Railway line (Figure A3.3). Weather conditions were near-perfect for seismic data collection, with no wind and water-saturated, near-surface conditions, from several days of rain in the preceeding week. The survey was undertaken with two field personnel. The test took place in a large, fenced, deer paddock on the Burnside Farm. The paddock was well irrigated with short grass and no animals present during the tests. The near-surface material consists of short grass on unconsolidated 0.3m thick hummus-rich soil with only very few clasts of Torlesse and limestone (<<5%). Extrapolating from a nearby well log, the subsurface grades into silty very-fine sand and silty clay, which may be up to 20 m thick (Loris, 2000). Below this, the subsurface consists of inter-fingered layers of Torlesse and limestone, early to late Pleistocene gravels with silt/clay/sand layers. Below the gravels (estimated to be up to 260 m thick) is a sequence of mudstone/limestones and conglomerates with Torlesse basement (estimated to be 600-1000 m deep). The depth to the fully saturated zone has been measured using seismic refraction information to be 2-3 m.

Results:

Very simple processing of the raw shot gathers was undertaken. A window was chosen where the arriving reflection energy was uncontaminated by air-blast or ground roll energy (100-220 ms in the far offset geophones) and the frequency spectrum derived (Figure A3.4). The spectrums were then normalised. The screw-in geophones show a greater proportion of their seismic energy at higher frequency especially in the 170-250 Hz range (Figure A3.4). They also show less 60 Hz harmonics, which is due to the short geophone lead-in wire length and screening of the steel geophone case. The results are affected by two problems with the test procedures. First, the control test, which used normal planted geophones, had to use a string of three geophones at each location as that was all that was available. The individual response of the geophones is therefore averaged at each location. This means that the amplitude of the signal collected is the sum of the geophone elements at each location and not the signal from a single element as in the screw-in geophone. The phase response of the planted geophones is also affected by the fact that the response is the sum of the responses of all the elements in the string. The individual elements have very similar phase responses but the elements are not in the same physical location and are planted slightly differently. The cumulative effect of these two differences is likely to be minor. At the frequencies that are transmitted through the subsurface at this location the difference in ray path distance is less than 1/20 of a wavelength. A direct comparison between the amplitudes of the planted and screw-in geophone is quite difficult to quantify due to this difference.

Conclusions:

The screw-in geophone increased the high frequency content of the reflection part of the recorded wave-field. This is believed to be because the geophone is located below the very near surface unconsolidated layer, which attenuates much of the high frequency content and the increased ground-geophone damping caused by increased geophone ground coupling. However, the screw-in geophone is unlikely to be developed further as its advantages can be equalled or surpassed with "normal" geophones and shallow drilling. The screw-in geophone may be useful if deeper geophone placement is required, and where manual planting of geophones in drilled holes is impossible or difficult.

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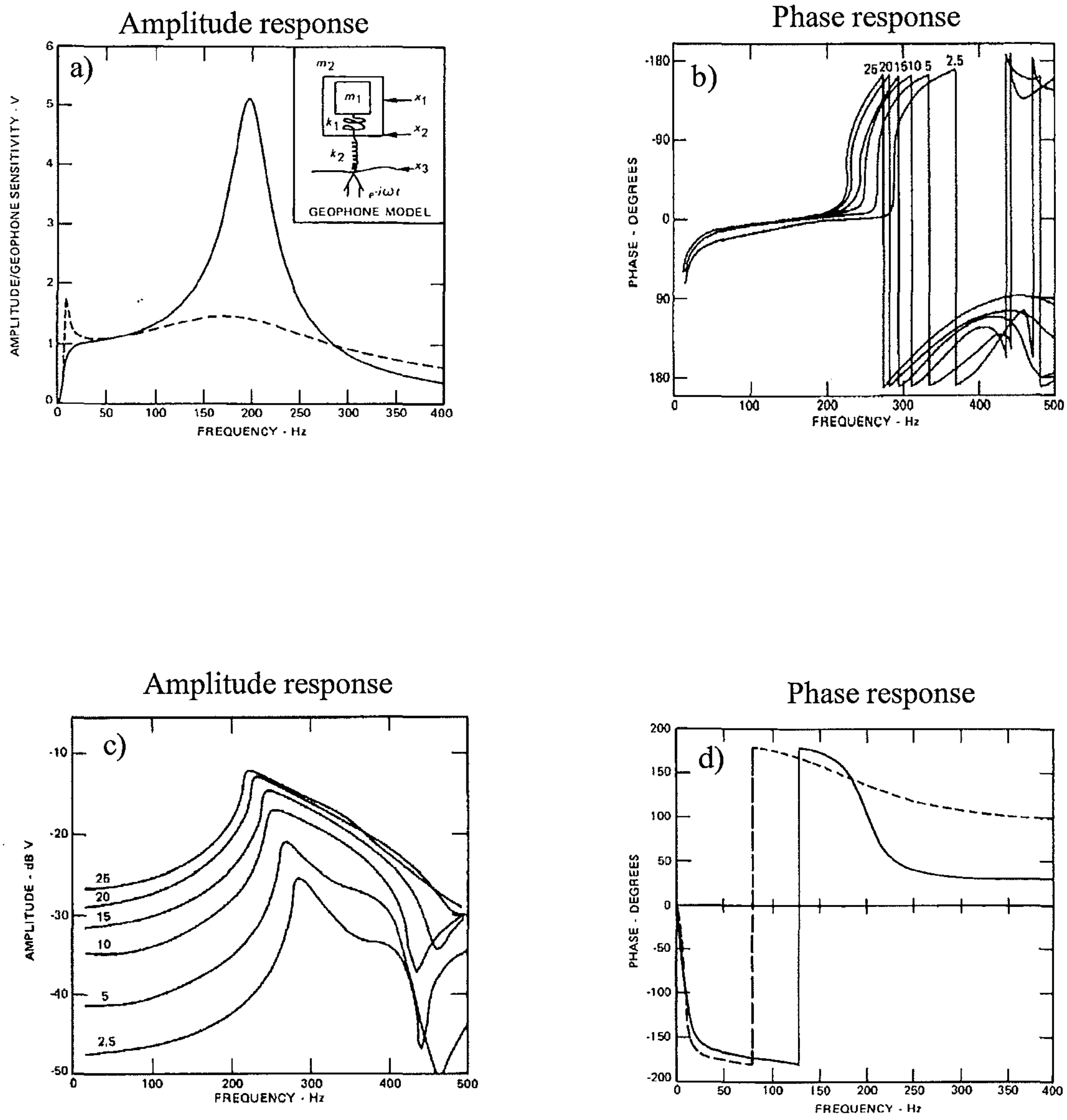

Figure A3.1: a) Modelled ground-coupled geophone amplitude response. b) Modelled ground-coupled geophone phase response. c) Measured ground-coupled geophone amplitude response for geophone planted in sand. d) Measured ground-coupled geophone phase response for geophone planted in sand. (Reproduced from Krohn, C.E 1985)

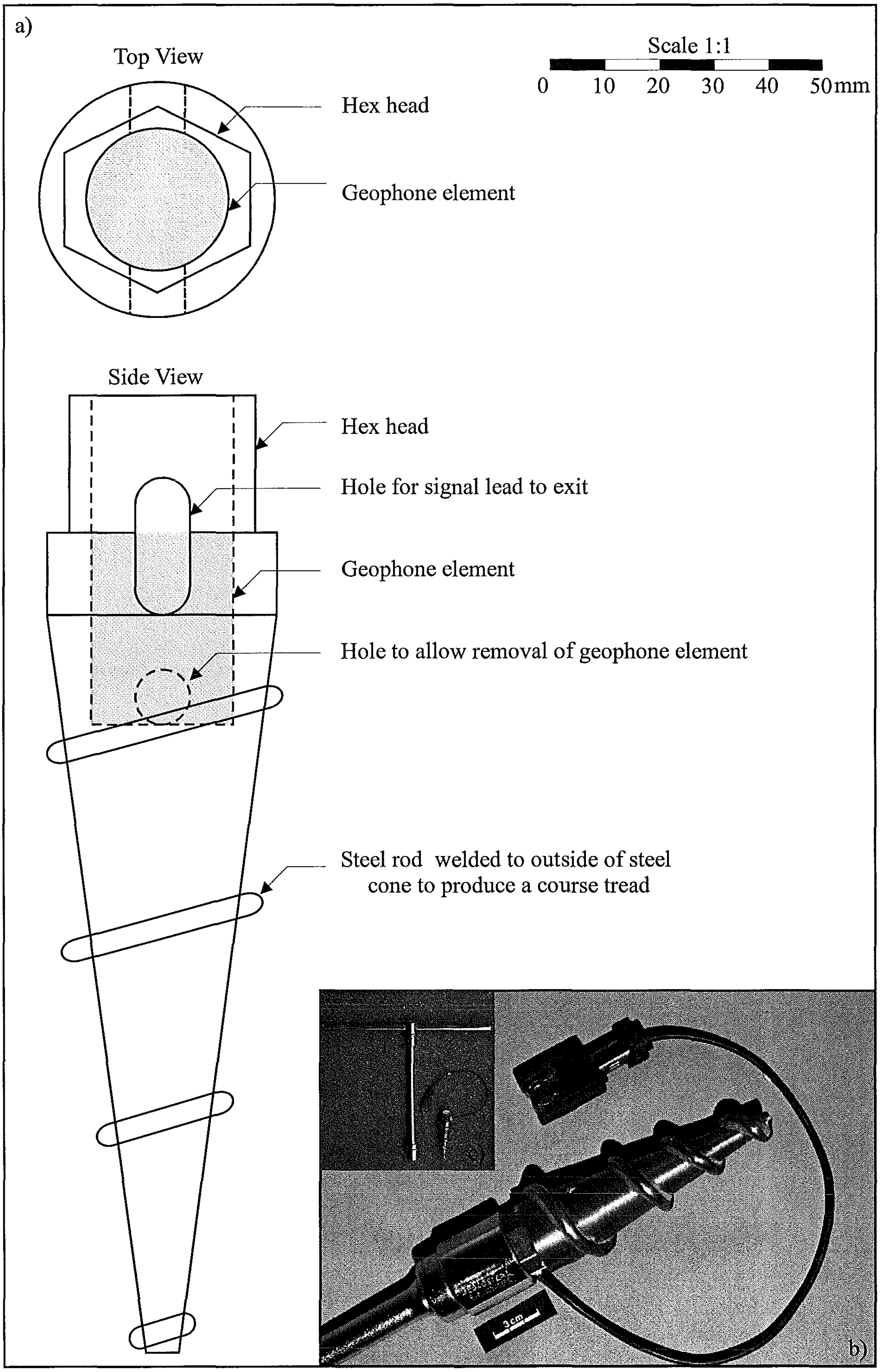

Figure A3.2: a) Top and side diagram of the screw-in geophone b) Photograph of geophone and socket c) Geophone and socket spanner

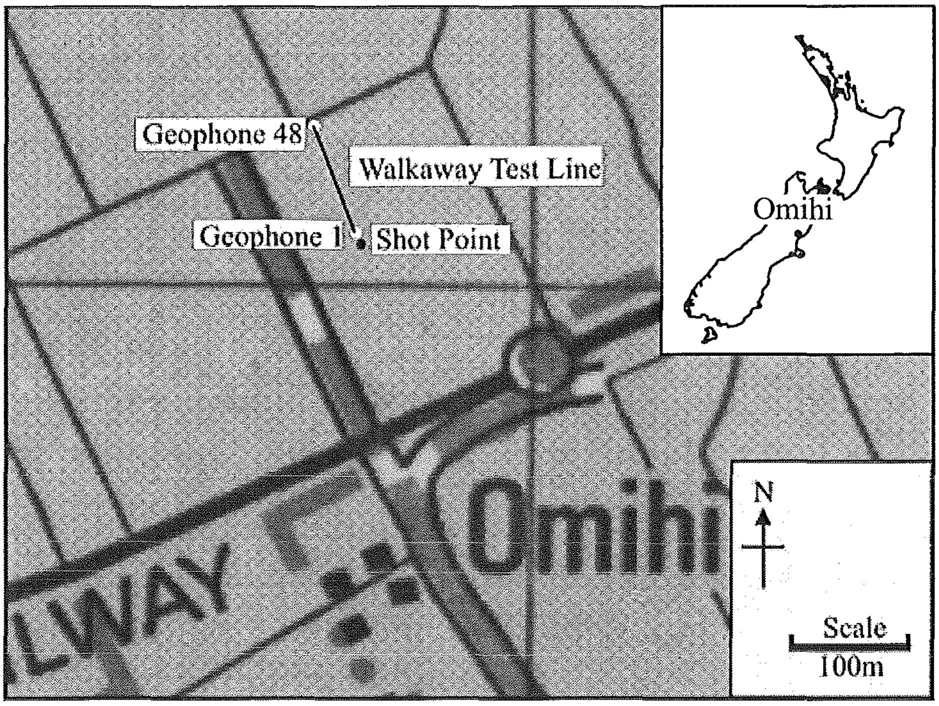

Figure A3.3: Map showing field test area, Omihi Valley, North Canterbury. Topographic map from Department of Survey and Land Information, 1:50000 series, Wellington, New Zealand

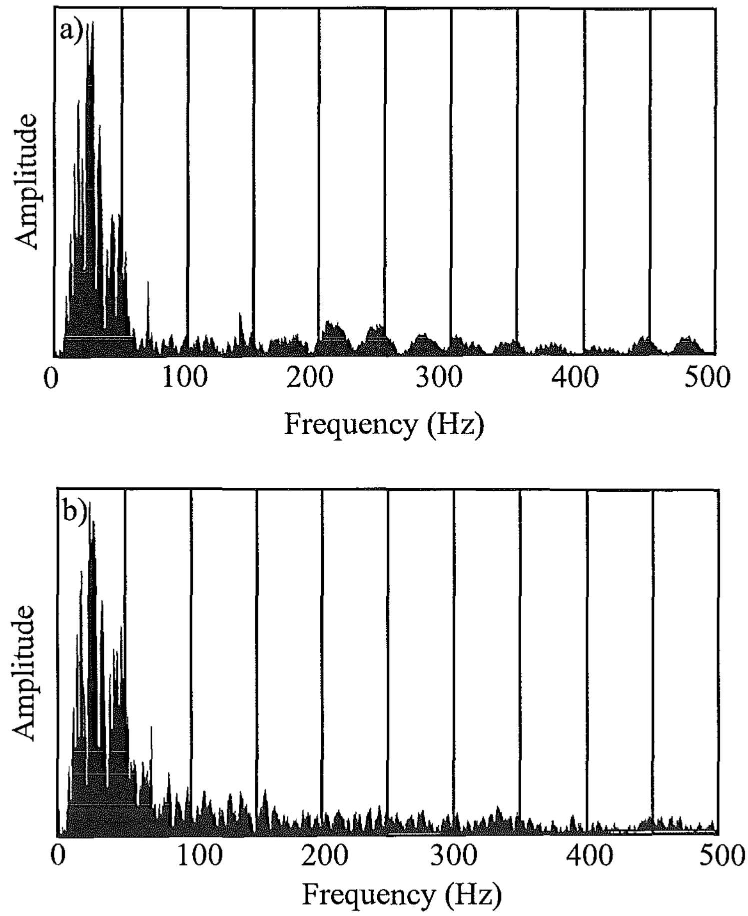

Figure A3.4: a) Normalised amplitude spectrum for "normal" planted geophone. b) Normalised amplitude spectrum for screw-in geophones.

Appendix 4

Comparison of electrokinetic and seismic reflection profiling in unconsolidated sediments, Omihi Valley, for hydrogeologic exploration

Summary:

This appendix describes research undertaken to evaluate the usefulness of electrokinetic sounding (EKS) in delineating high permeability/porosity units and paleo-fluvial structures within the Quaternary gravels of the Omihi Valley, North Canterbury. Two EKS profiles were undertaken where good subsurface information was available including high-resolution shallow seismic reflection profiles and logged boreholes. The EKS soundings were undertaken using a Groundflow © 300 instrument (Groundflow, 2002). A comparison of EKS soundings with borehole and seismic reflection/refraction data indicates a gross scale correlation between the EKS and seismic reflection/refraction boundaries. The actual electrokinetic physical mechanism appears poorly understood and therefore an informed interpretation and correlation with the seismic and borehole data is impossible. The EKS instruments operating range of 0-100 m using a hammer and plate source is too shallow to be of use in delineating economic aquifers in many areas of North Canterbury and if the method can be demonstrated to be successful, it will need to be extended for greater depths.

Electrokinetic Seismic Profiling:

The EKS method is a relatively new, applied geophysical method and the correlation between the seismic impulse and the electromagnetic signal is not fully understood (Butler et al., 1996). Although the theoretical principles of the EKS method have been developed, the qualitative and quantitative dependence of the EKS signal on subsurface geology, rock properties, and fluid and gas saturation are currently only poorly defined.

Thompson (1936) first proposed the use of coupled seismic and electrical energy as an exploration tool (Thompson, 1936). The method involves the conversion of seismic wave energy into electromagnetic wave energy in the subsurface. The seismic wave energy is generated in the same way as in standard seismic methods, with an impulse into the ground such as a weight drop or explosive. This impulse generates a P-wave (and other coherent wave energy), which propagates with spherical divergence into the subsurface. When the seismic wave reaches a contrast in acoustic impedance a portion of the incident wave is converted into a Biot slow P-wave. The Biot wave generates differential movement between the pore fluid and rock matrix. This differential motion distorts the electric dipoles on the mineral surfaces. The charge separation generates an electric field known as the streaming potential. The time variant electric field interacts with the Earth's field generating a disturbance which propagates to the surface where it is detected by an array of field electrodes. In theory the rise time of the streaming potential is inversely proportional to the rock/sediment permeability (Chandler, 1981). The Groundflow © 2000 EKS instrument uses proprietary algorithms to convert the received electrical signal into hydraulic conductivity.

The electro-seismic response is dependent on the motion of ionic fluid flow through the pore spaces of the rock matrix. Depending on the rock matrix and ionic fluid, either cations or anions will adhere to the pore walls. Therefore, differing ionic fluid and rock matrix mixtures will result in different electric dipoles (+/-) and hence, the generation of different polarity electrokinetic fields. Field work undertaken by the British Geological Survey using similar Groundflow© equipment indicates that "existing interpretation routine (supposedly yielding absolute permeabilities and borehole cumulative flow) was too ambitious in view of the large range of variables involved and the complex nature of the inducing seismic pulse" they therefore limited their interpretation "to a qualitative indication of likely permeable horizons based solely on the rise-time of the EKS signal" (Peart, 1997). This procedure has been followed in this appendix, and only qualitative relative hydraulic conductivity profiles are presented.

Method:

On the 6th June 2000 two separate short EKS profiles were undertaken, profile 1 and profile 2. The EKS equipment, a Groundflow © 300 instrument was supplied by the Australian Nuclear Scientific & Technical Organisation (ANSTO) and operated by Stuart Hankin. The profiles were located along Omihi seismic line 3, near two logged boreholes (N34-144 and N34-150) (Figure A4.1). The acquisition parameters used for the two profiles are shown in Table A4.1, and the field equipment in Figure A4.2.

	Profile 1	Profile 2
Number of shot points	5	6
Source	Hammer and plate	Hammer and plate
Shot point spacing	25 m	25 m
Number of stacks	8	8
Inner electrode spacing	0.5 m	0.5 m
Outer electrode spacing	2 m	2 m

Table A4.1 Acquisition parameters for the two EKS profiles.

Six EKS soundings (EKS 1-6) were undertaken near the N34-144 well, and five adjacent to the N34-150 well (EKS 7-11). The location of the shot points and EKS antennas were measured using differential GPS to an accuracy of +/- 1m horizontally. Weather conditions were optimum for seismic source penetration, with good near surface saturation after rain during the previous week (but no surface water present), low wind speeds, and cool (<10C) temperatures.

Seismic reflection section and borehole log results:

Stratigraphic and structural control along a transverse valley profile adjacent to the EKS soundings is good, as a high resolution seismic reflection profile was obtained across the valley at this location (Omihi seismic reflection line 3) (Figure A4.1). The seismic profile was correlated against logged boreholes located at the locations of the two EKS profiles (see Appendix 7 and Figure A4.3). The two boreholes were not developed into producing wells because of the development/operational costs, but the wells were not dry. Both wells had many minor producing horizons, and an estimated production capacity of ~100 L/min. Quantifying the saturation of the subsurface units is impossible from recovered samples due to the rotary foam drilling method, but the drillers experience indicated that the units drilled through are saturated, as the drilling fluid inflow and outflow appeared balanced or slightly positive. Seismic refraction processing of the reflection data adjacent to the EKS survey locations indicates that the depth to water table at both EKS profile locations is 4.5 m +/- 2 m.

Electrokinetic profile results:

Conversion of the EKS survey data from time to depth is calculated using a constant interval velocity of 2000m/s. This is a reasonable estimate of the average velocity over the depth of the profiles, but does not take into account the rapid increase in velocity from saturated to unsaturated sediments. This jump in P-wave velocity can be 1-5 times as the sediments approaches 100% saturation. The subsurface sediments also undergo compaction giving rise to a general increase in velocity with time. A more realistic conversion of time to depth derived from seismic reflection semblance velocity analysis would be using a linear velocity increase from 1600 m/s at the surface to 2000 m/s at 100 m depth.

The EKS results for the survey profile 1 undertaken next to well N34-144[1] appear to indicate that the major portion of the EKS response occurs within the top 20m at this location (Figure A4.4). This response is believed to be related to the unsaturated zone and may represent the strong EKS response of unsaturated material (Hankin, per. comm., 2001). Within the top 20 m the relative hydraulic conductivity appears to be laterally highly variable. This response may be related to the sand units within the top 20 m seen on N34-144 well log. These would have a high hydraulic conductivity if not loaded with clay and silt, but the percentage of clay appears to be too high (>70%) to define this zone as highly permeable (Appendix 7). The zone of very low hydrologic conductivity at EKS location 5 at 75 m is of unknown origin but may represent a zone of very tight clay bound gravels, but is interpreted as a poor antenna coupling problem by the operator. The EKS profile 2 located next to well N34-150 shows two zones of high hydraulic conductivity in the top 20 m (Figure A4.5). These are located at 0-5 m and 10-20 m and may correspond to the unsaturated near surface zone (0-5 m) and a transition into water bearing limestone gravels (10-20 m).

Discussion:

The valley-fill Quaternary geology in the Omihi Valley is highly complex. It consists of a complex geometry of inter-fingering paleo fluvial channels, over channel deposits, and valley margin alluvial fans (see Chapter 2). This complexity results in rapid vertical changes in lithology (Figure A4.4 and A4.5 borehole logs). From similar depositional environment analogs seen in outcrop, it is assumed that the subsurface is similarly laterally highly variable. Due to the inherent frequency limitations of seismic reflection method, the depositional structures and units tend to be averaged at lateral and vertical scales smaller than the resolvable limit of the seismic reflection method. These resolution limits result in what appear to be similar imaging limits for both the EKS and seismic reflection surveys. The EKS profiles 1 and

[1] *Note: The wells are named N34-144 and N34-150, but do not appear in the Environment Canterbury wells database, as they were not developed to production, and their casings were pulled after drilling. The well names may be reused at a later date for new wells drilled in the area.*

2 appear to give a gross scale image of the subsurface, and appear to have resolution for the near surface (0-25 m) approaching the seismic reflection resolution (2 m). The subsurface in the location of the two profiles is known from drill and seismic data to be highly variable in porosity and permeability, however, this is not detected on the EKS profiles. Whether this is an inherent averaging of the response from a volume of the subsurface with the EKS method or an inability of the EKS method to image porosity/permeability variations is unknown.

The EKS method also appears to have limited penetration using the hammer and plate source in this area (~100 m). This is in contrast to the standard reflection method which is able to penetrate to >300 m with relative ease. This implies that the EKS signal needs a stronger seismic impulse to generate an electromagnetic signal which is discernable at the surface electrodes. The inability of the electromagnetic signal to reach the surface may also be due to the high conductivity of the gravels in the area. All major productive wells in the Omihi Valley are producing from ~100 m depth. The EKS method as applied in this experiment was unable to penetrate to these depths. Its use may therefore be limited unless a more powerful seismic source is used.

Future work:

To fully evaluate the EKS method for use in the glacial fluvial gravel sediments of North Canterbury further surveying using the EKS method is required. Ideally the test site would consist of a well (50-200 m deep) that has been logged for porosity and permeability. The well should have several discrete producing horizons and be PVC-cased so the metal of the drill casing does not affect the EKS results. To reduce the effect of ground-roll, which is believed by some authors to be the major mechanism of generation of the EKS response (Butler et al., 2002), a below ground explosive source should be used. This will reduce the ground roll effect and increase any P-wave reflection EKS response. For example, a comparison between a 5 kg Hammer and 12-gauge blank shell gives a 3:1 reduction in ground-roll, with similar air blast and reflection signal strengths. To further reduce the effect of ground-roll and other coherent wave energy, the EKS electrode geometry should also be altered between shots to simulate electrode equivalent of geophone arrays.

Conclusions:

The use of EKS to delineate changes in the subsurface hydraulic conductivity has not been proven in the Omihi valley. The EKS survey profiles show some large scale structural similarity with seismic reflection derived structure and lithology, but without very closely spaced logged boreholes the lateral and vertical features seen in the EKS profiles can not be convincingly identified.

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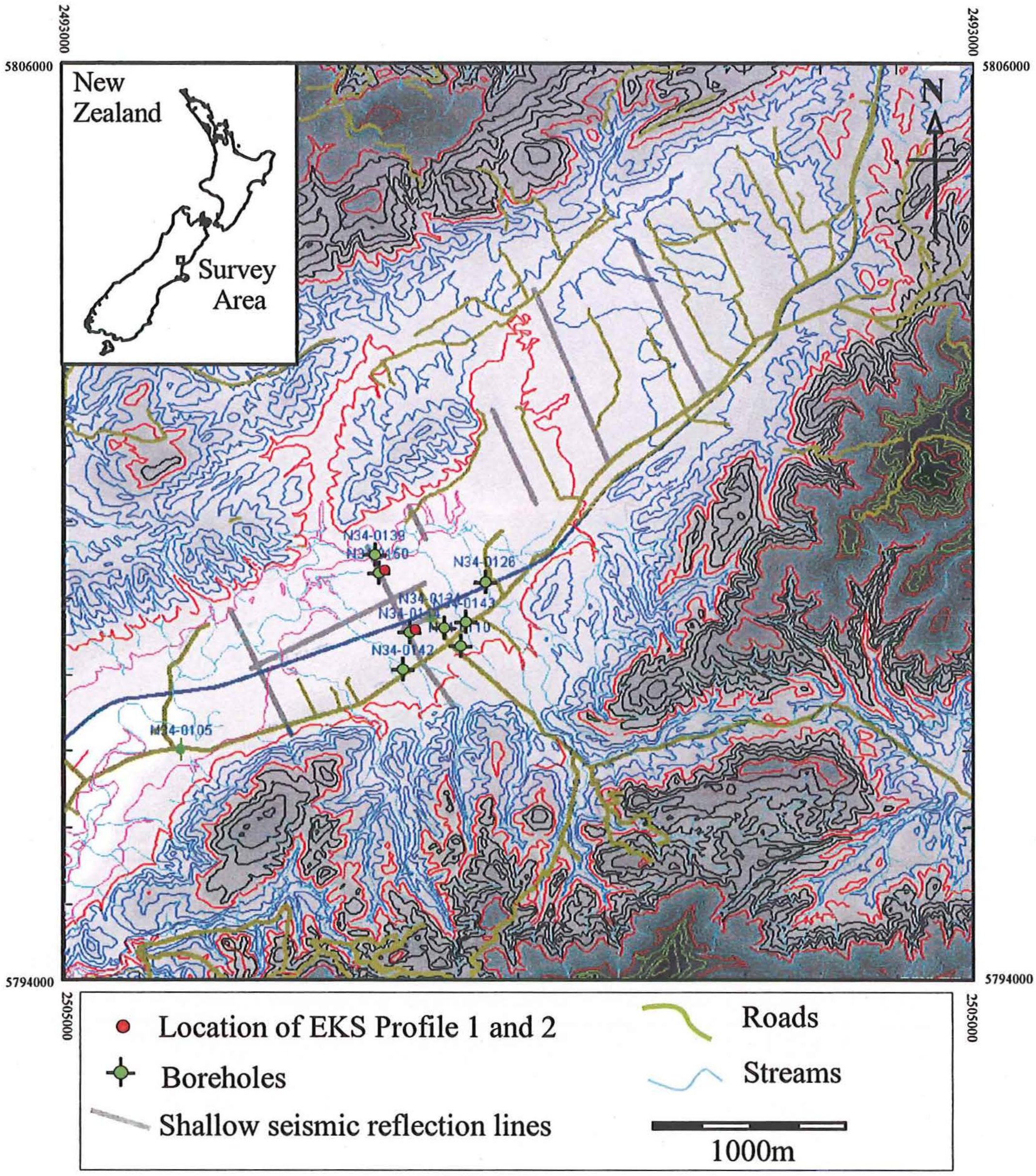


Figure A4.1: Location Map showing position of EKS profiles 1 and 2, and the location of all seismic lines within Omihi Valley. Map base from NZMS 260, N33 Edition 1 1984, Published by Land information, New Zealand.

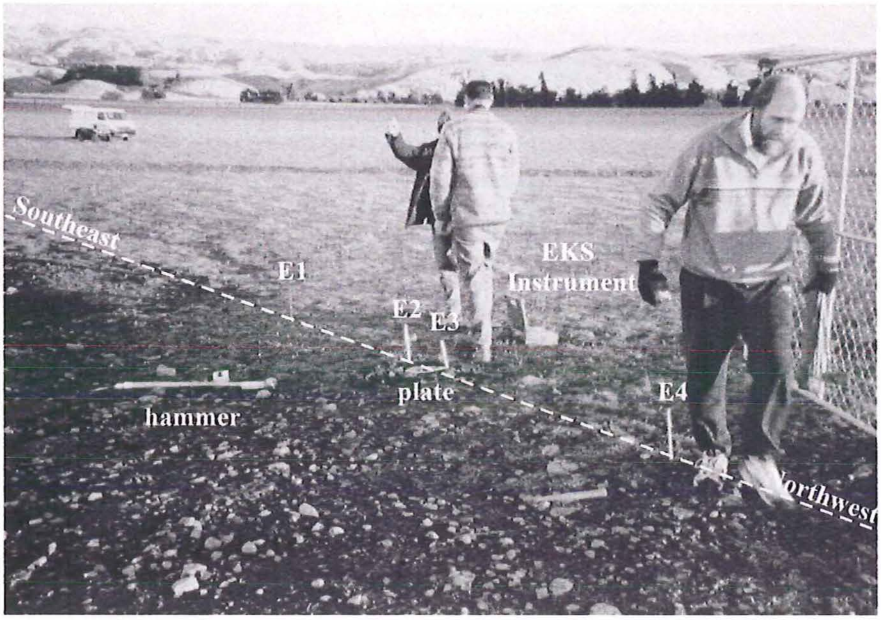
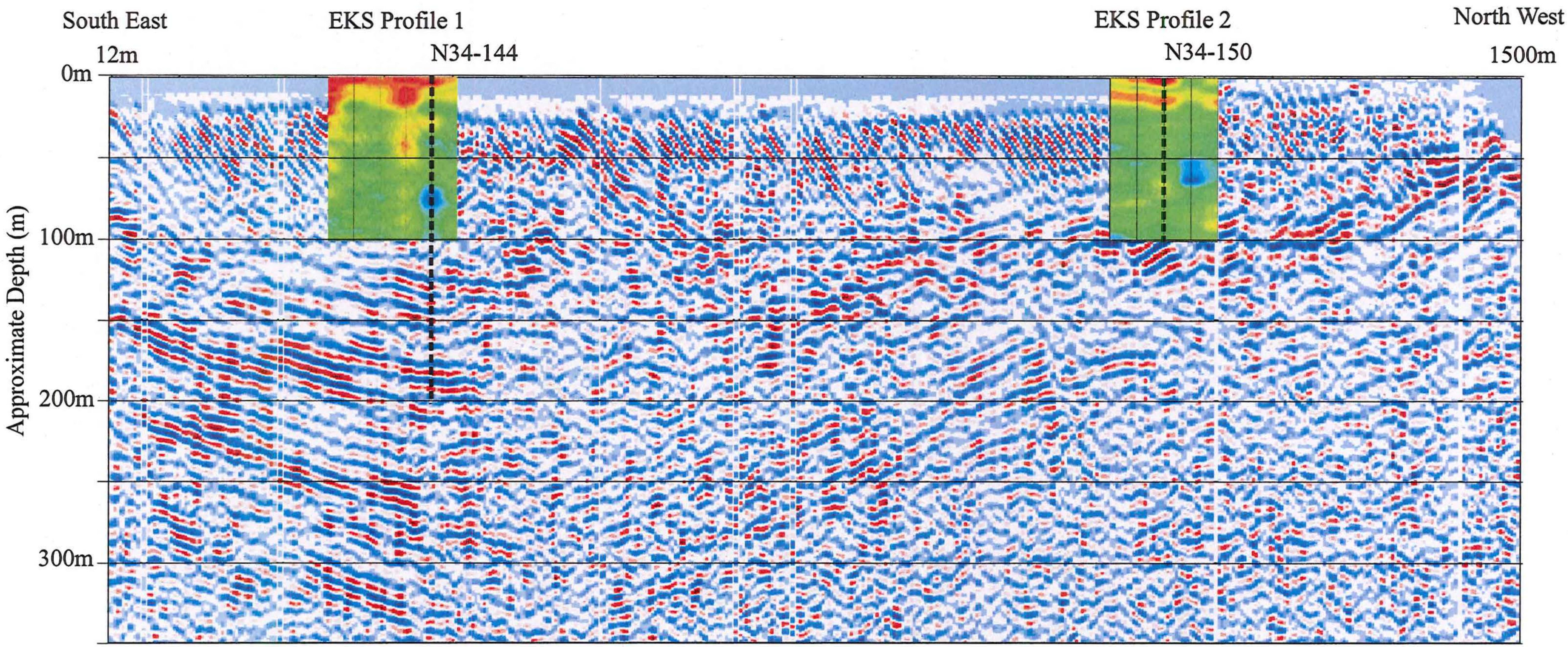


Figure A4.2: Photograph of EKS survey with EKS instrument, hammer and plate source and electrodes E1-E4 shown. Dotted white line shows the strike of profile.



Shallow seismic reflection line Omihi 3

Figure A4.3: EKS profiles 1 and 2 overlayed over Omihi 3 shallow seismic reflection line.

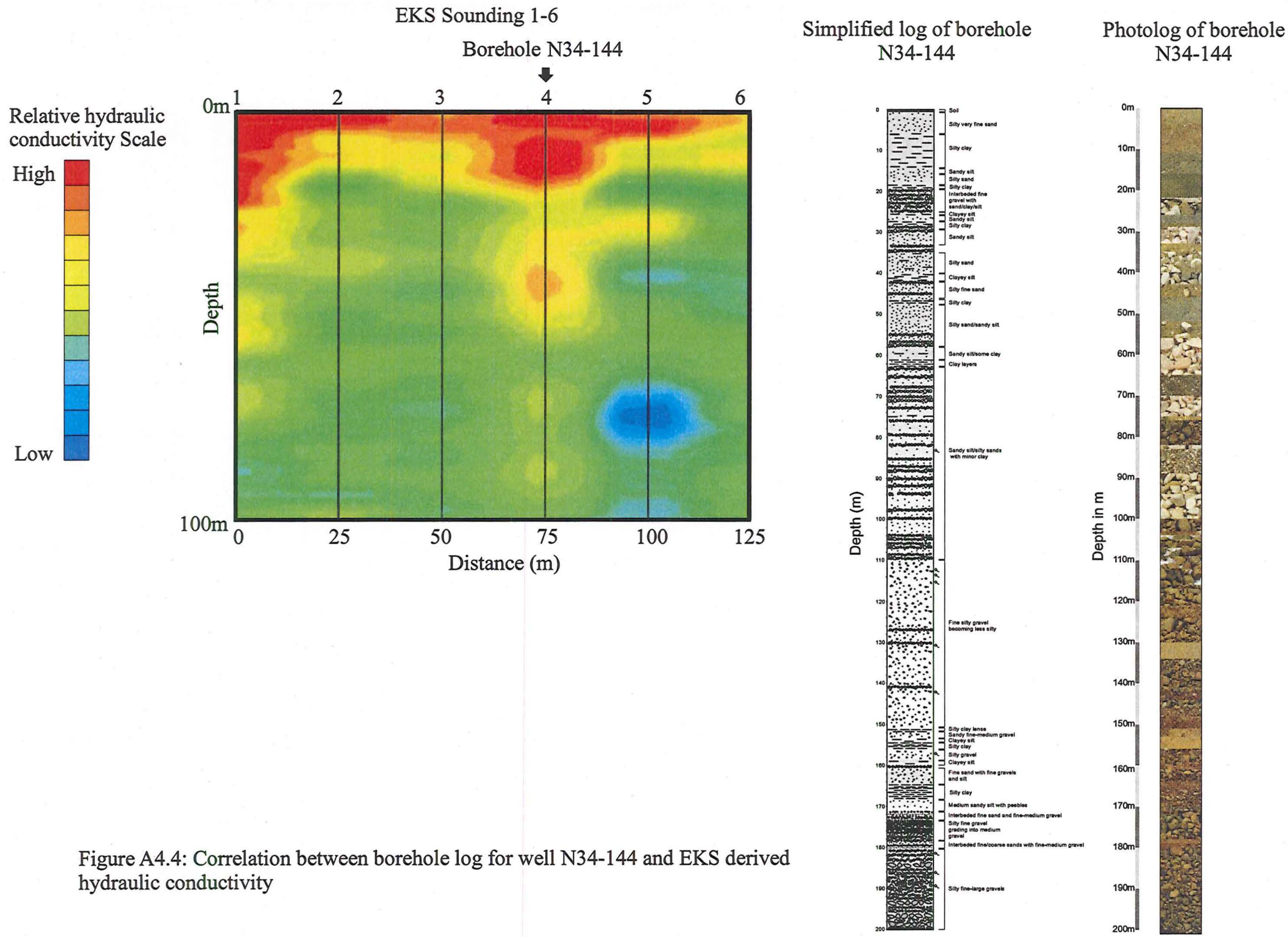


Figure A4.4: Correlation between borehole log for well N34-144 and EKS derived hydraulic conductivity

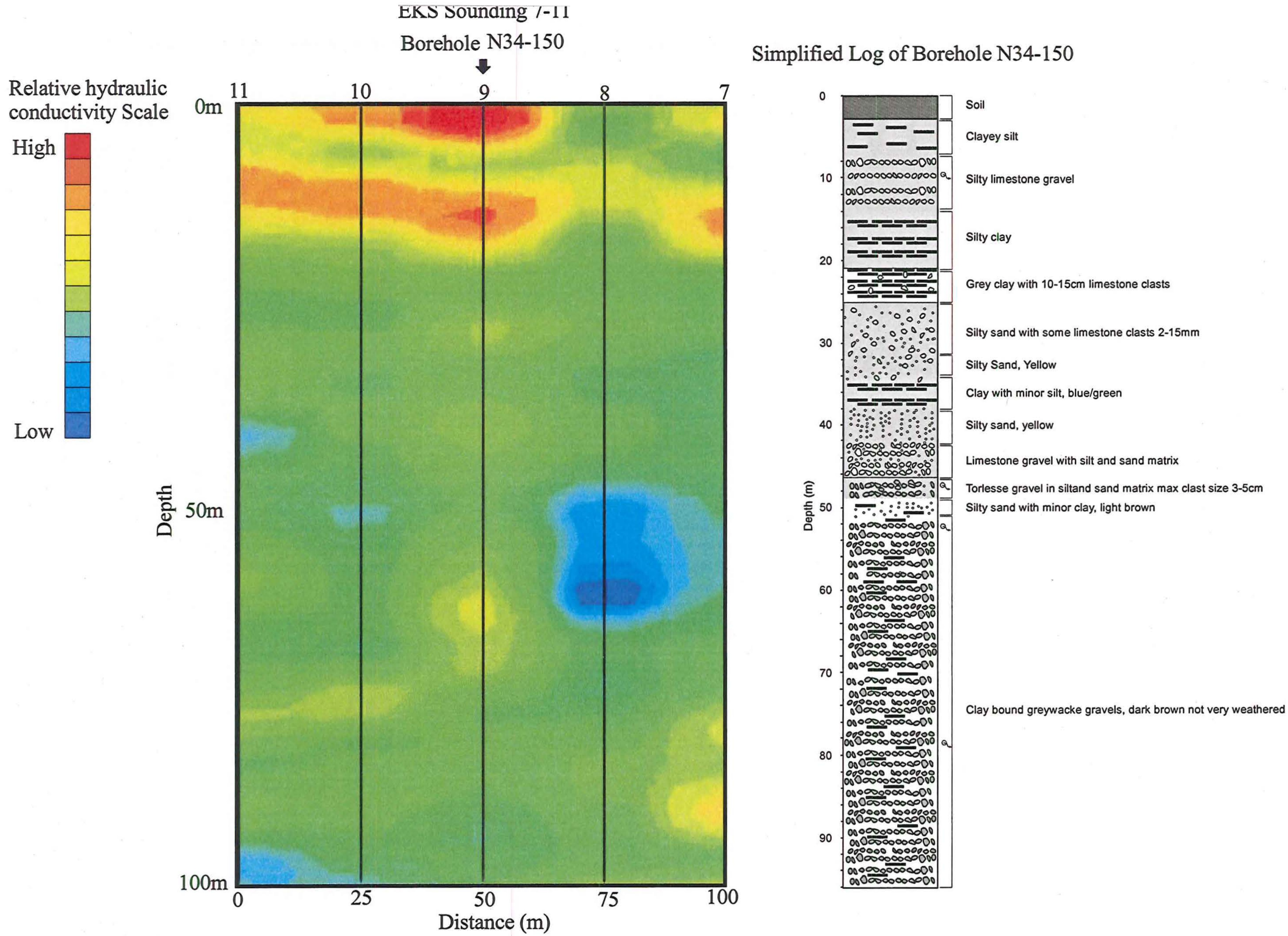


Figure A4.5: Correlation between borehole log for well N34-150 and EKS derived hydraulic conductivity.

Appendix 5

A comparison of seismic reflection profiles with transient electromagnetic, gravity and resistivity surveys, Omihi Valley North Canterbury

Summary:

The Omihi Valley is one of the few locations where Transient ElectroMagnetic (TEM), resistivity surveying and gravity surveying has been undertaken, and where good quality shallow seismic reflection and borehole data is also available. It therefore offers an opportunity to compare TEM, resisitivity and gravity based models for a valley with a well constrained surface outcrop geology, and subsurface borehole and shallow seismic reflection model. The key results derived from this comparison are:

- The seismically defined model for the valley could not be reconciled with the model defined using gravity data. This is believed to be because of rapid lateral and vertical lithological changes in the Tertiary sequence underlying the Omihi Valley, as this variability will tend to mask any basement paleotopography.
- Resistivity was unable to penetrate to useful depths (eg) due to the probe separations used and therefore within the valley, the data is of little use.
- The TEM data shows a good correlation with the seismically defined model and may offer a useful geophysical method to delineate the Quaternary gravel lithology when used in conbination with seismic reflection surveying and borehole logging.

Previous Work:

TEM, gravity and resistivity surveys were undertaken in 1999 by the University of Canterbury fourth year geophysics class. These surveys were carried out adjacent to the Omihi School along Reece's Road and the Burnfoot Farm entranceway (Ghozali and Mullen, 1999). Further TEM and gravity surveying was later undertaken by Loris across the Glenrose and Spye properties in the North of the Valley (Loris, 2000). The class surveys resulted in six

TEM and resistivity soundings, and thirteen gravity points. The survey locations were spread along a 1200 m transect perpendicular to the valley's axis. Loris surveys (farther to the North) consisted of nine gravity stations spread along a 900 m transect adjacent to the eastern valley margin, and perpendicular to the valley's axis. Three TEM surveys were also undertaken along the same survey line (Figure A5.1). (Detailed results from these surveys and acquisition parameters can be found in (Loris, 2000).

Seismic reflection surveys:

The seismic lines Omihi-3N, Omihi-3S and Omihi-5 are located adjacent to the Reece's Rd-Burnfoot Farm and Glenrose-Spye TEM, and gravity survey transects. The Omihi-3N and 3S line orientation is not identical to the gravity profile direction but is offset south-west by 500 m at the southern end and 50 m at the northern end. Omihi-5 at the northern end of the valley is located 200-300 m northeast of the Glenrose-Spye TEM transect and has a parallel orientation. The location for the Glenrose-Spye TEM surveys is only generally known and so correlation with Omihi-5 is only qualitatively possible. The acquisition and processing parameters of the seismic lines are fully documented in Part II of this thesis.

Results :

Resistivity surveying - Burnfoot Farm -Reece's Road, Omihi Valley

The electrode spacing used for the Wenner array resistivity surveys located along the Burnfoot Farm -Reece's Road transect was 42-56 m (Ghozali and Mullen, 1999). This gives a current electrode spacing of 126-168 m. Assuming a standard half space model, the penetration achieved is generally assumed to be 25-33 % of this separation, or 31.5-56m (Parasnis, 1979; Barker, 1989). This penetration means that most of the resistivity soundings are within the muted refraction zone of the seismic reflection sections and so can not be compared with the seismic reflection data. Therefore no further analysis was undertaken on the resistivity soundings.

Gravity survey - Glenrose-Spye

The residual gravity readings show a general decrease from southeast to northwest along the Glenrose-Spye transect with a high located about 600 m from State Highway 1 (Figure A5.2). This high represents only a 1.2 mgal deviation, but is statistically valid as the mean standard deviation for the readings is 0.05 mgal and corrections for terrain, elevation, latitude and drift have been applied.

Gravity survey - Reeces Road

The Burnfoot Farm-Reeces Road gravity transect indicates a general increase in the residual anomaly from southeast to the northwest (1.6 mgal anomaly) (Ghozali and Mullen, 1999).

TEM survey Reece's Road - Burnfoot Farm

Results from seismic survey Omihi-3N and Omihi-3S and the Reece's Rd-Burnfoot Farm TEM soundings are shown in Figure A5.3. Depth conversion for the seismic used a constant 2000 m/s interval velocity model, while the TEM soundings were depth converted using the standard Temix-GL© analysis routines. The seismically defined depths are likely to be accurate to +/- 20 % and the TEM +/- 10 %. Due to these errors direct comparison between events is limited to large scale changes.

Glenrose-Spye TEM surveys

The TEM soundings TEM-1, TEM-2 and TEM-3 show a resistive layer approximately 40 m thick with a more conductive layer below. This layer appears to thicken to the southeast. Due to inaccurately recorded location of the TEM profiles no detailed correlations can be drawn at this location.

Synthesis and conclusions:

Gravity survey - Glenrose-Spye

The gravity model derived by Loris is not in agreement with the seismically defined model and shows a topographic basement high which is not seen in the seismic data (Figure A5.2).

Gravity survey - Reece's Road

This anomaly is small and may be affected by operational error due to inexperienced operators and data processing. The survey contradicts the mapped geology, subsurface borehole and seismic reflection data.

The main use of this gravity survey is to demonstrate that the use of gravity for shallow sedimentary basin work requires extreme care during data collection, a high resolution instrument, small station spacing and careful data processing.

The use of gravity modeling within the basin is extremely difficult as the Tertiary sequence underlying the Quaternary gravel cover is known from drill and outcrop exposure to consist of shallow marine depositional units which are highly heterogeneous. Modeling of the sequence as a single unit is therefore unlikely to yield realistic results. For the above reason further comparison of the gravity and seismic reflection results were not undertaken.

TEM

The TEM soundings have defined the major lithologic boundaries within the Quaternary gravel sequences (Canterbury, Teviotdale, Kowai Formation) and possibly the Tertiary Mt Brown Formation. It appears the Canterbury gravels have a low resistivity and are more conductive than the lower Tevoitdale and Kowai gravels. This is believed to be because of the more mixed lithology with high limestone content and less weathered Torlesse gravels and the higher clay content of the Kowai and Tevoitdale gravels.

Below this, the resistivity increases, probably due to the gravels being more consolidated and weathered, and containing only very minor limestone or non-Torlesse derived material. Penetration below the Canterbury/Teviotdale interface is limited (only TEM-1) but the underlying resistive sequence appears to be thick and may represent the Kowai/Mt Brown Formations.

The orientation of the two seismic lines is similar to the two TEM and gravity transects, but is offset by several hundred metres laterally, making correlation between small laterally variable geologic units and structures difficult. A further complication is the depth error inherent in the seismic and TEM processing methodolgy. Any correlations therefore are limited to valley scale major depositional/erosional changes and structural elements.

The correlation between the seismically defined Canterbury/Teviotdale interface and the TEM defined horizon implies that the TEM method is capable of imaging the Canterbury/Teviotdale horizon. This horizon is important in the Omihi Valley, as it is the zone at which most economically viable aquifers are located. The TEM's relatively fast acquisition rates and large lateral coverage appears to offer an economic method of initial hydrologic exploration. This result is in agreement with the work undertaken in the North Culverden Basin by Armstrong (Armstrong, 2000).

References:

Armstrong, M. J., 2000: Geomorphological and geophysical investigation of the effects of active tectonic deformation on the hydrogeology of North Culverden Basin, North Canterbury [Ph.D. thesis]: University of Canterbury, Department of Geological Sciences, 211 p.

Barker, R. D., 1989: Depth of investigation of collinear symmetrical four-electrode arrays: Geophysics, v. 54, no. 8, p. 1031-1037.

Ghozali, D., and Mullen, M., 1999: Geophysical Investigation of the Omihi Fault: University of Canterbury, Department of Geological Sciences, 18 p.

Loris, P., 2000: Hydrogeology of the Waipara alluvial basin [M.Sc. thesis]: University of Canterbury, department of Geological Sciences, 207 p.

Parasnis, D. S., 1979: Principles of applied geophysics: London, Chapman and Hall, 275 p.

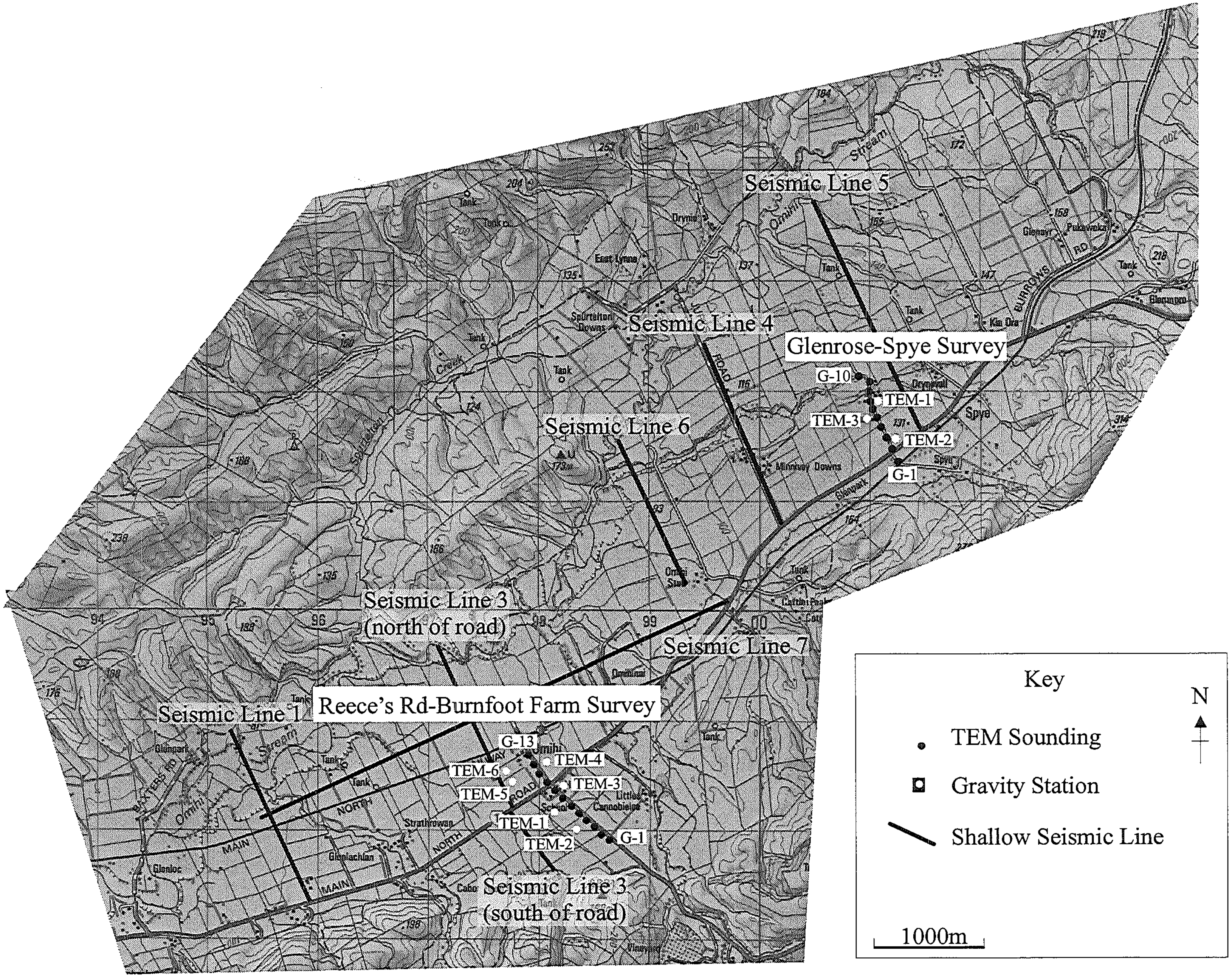
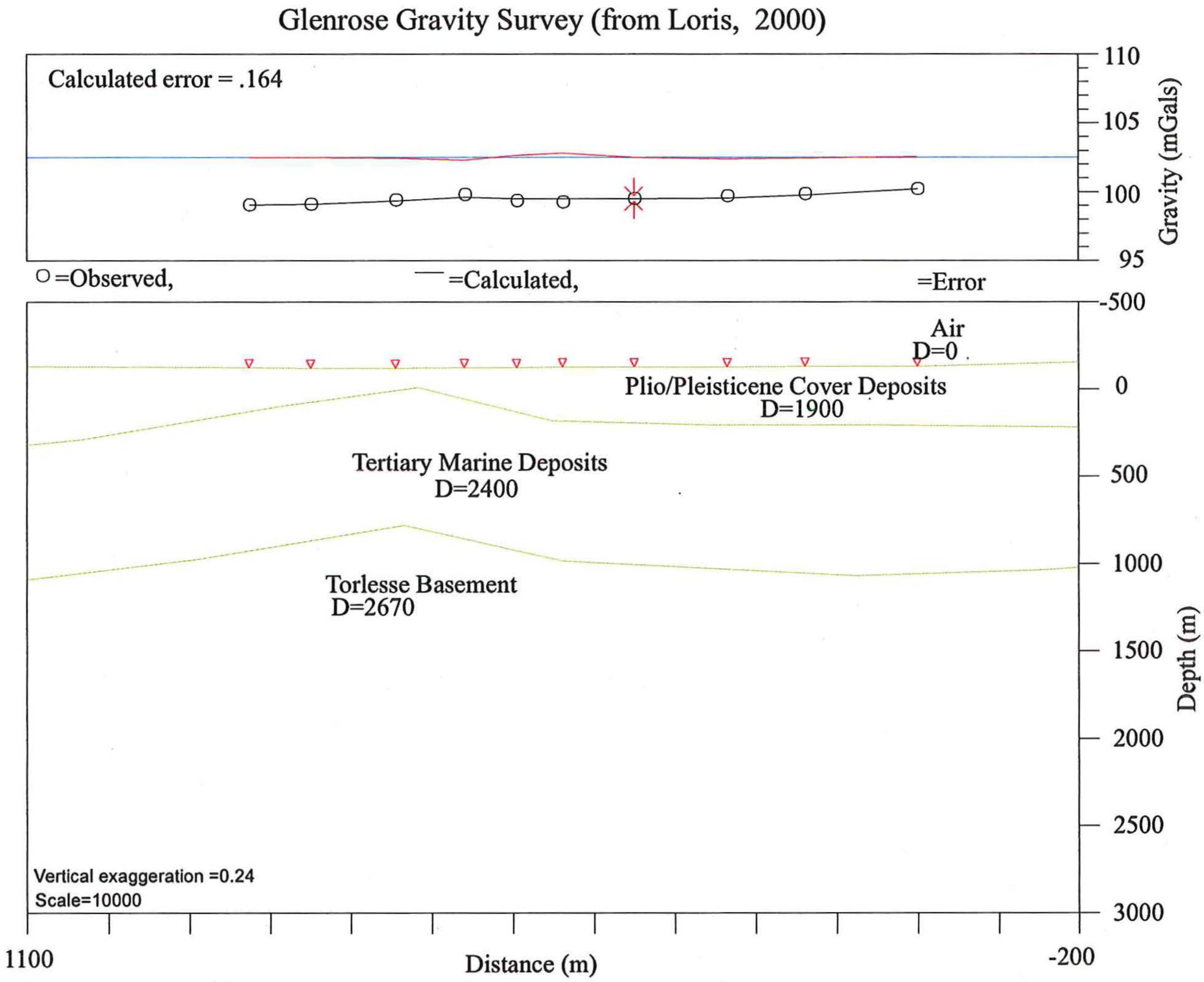


Figure A5.1 Location of the Reece's Rd-Burnfoot Farm and Glenrose-Spye TEM and gravity surveys.



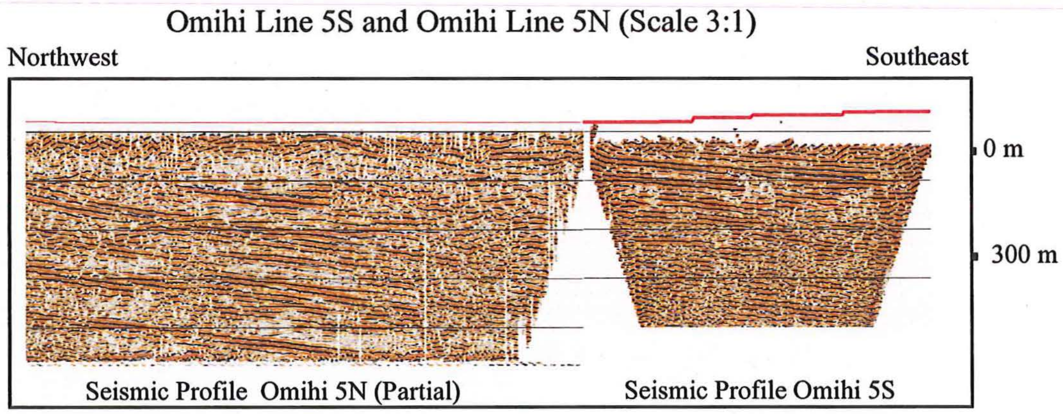


Figure A5.2 Glenrose Gravity Model and Omihi Line 5S,5N shown at the same scale

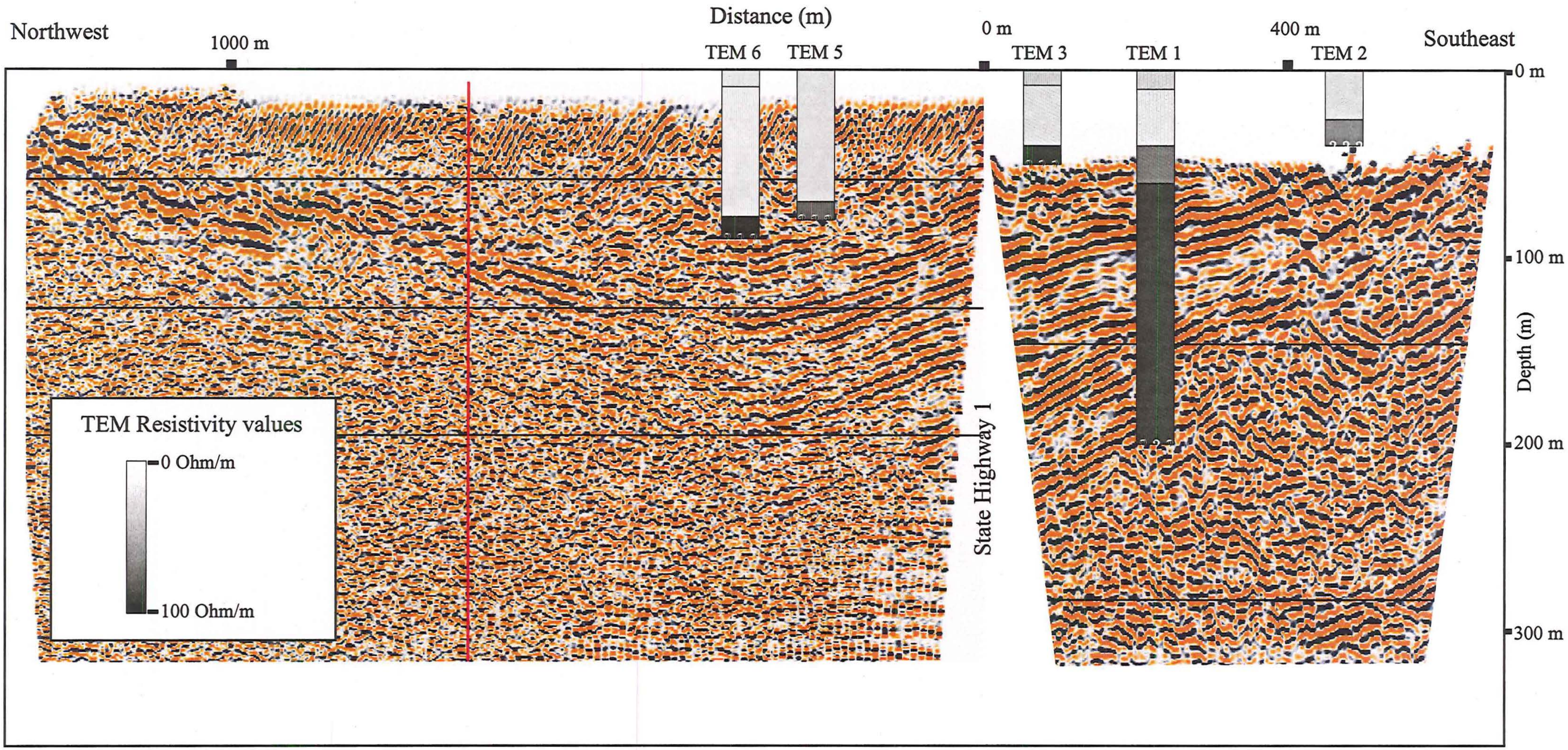


Figure A5.3 Omihi Line 3 north and south of the State Highway 1 with TEM soundings 1-6 overlain.

Appendix 6

Active source shallow seismic P-wave reflection surveying in an unconsolidated sedimentary environment

Introduction:

This appendix summarises the methodology used for shallow seismic reflection surveying in the North Canterbury unconsolidated fluvial/glacial sediments, and the seismic processing flows used to produce the final, stacked sections. It is not intended to be a comprehensive description of the seismic reflection method, which has been extensively covered by previous authors, Yilmaz (1987), Steeples et al. (1997), Steeples and Miller (1998) and Anderson (2000) but is an additional guide specific to working in the North Canterbury environment. It represents experience derived over the years 1999-2003, during which time over thirty kilometres of high resolution seismic reflection surveying was successfully undertaken.

Active source, seismic reflection surveying has been in use successfully world-wide since 1921, when it was first applied in Oklahoma, USA. The aim of a seismic reflection survey is to image, as accurately as possible, the subsurface stratigraphic, lithologic and structural details, with a minimum of field effort and associated costs to meet the criteria of the survey. Due to its successful use in hydrocarbon and mineral exploration, the development of acquisition equipment and processing algorithms has progressed rapidly and now allows detailed, temporally variable, three-dimensional images to be obtained.

Until recently the use of the seismic reflection method for shallow targets was limited, due to high equipment and processing costs. With the advent of cheaper, digital, high dynamic range seismographs, using off-the-shelf components and personal computer-based hardware, the use of the seismic reflection method has greatly increased in near-surface environmental, geologic and hydrogeologic investigations (Steeples et al., 1997). The shallow seismic reflection method derives many of its field and processing strategies directly from the oil exploration industry, but care must be taken as many of the assumptions used in "normal" deep seismic processing become invalid as the depth of interest shallows (Brouwer and Helbig, 1998). What is considered noise in deeper seismic surveys becomes the seismic signal of interest for the shallow subsurface.

Principles of seismic reflection surveying:

There are four principal stages in any seismic reflection survey:-

Design: The initial stage, usually undertaken before any field acquisition, is preliminary theoretical modeling and calculation of field acquisition parameters. The theoretical modeling is based on any known subsurface information, estimates of subsurface geology and lithology, and the aims of the survey. The theoretical field parameters are then used as initial first estimates of the acquisition parameters. The parameters are then further refined by field seismic walkaway testing.

Acquisition: The next stage involves the field collection of the seismic wave field data, using the best possible acquisition parameters, taking into consideration economy and efficiency.

Processing: Stage three aims to enhance the P-wave reflection component of the collected seismic wave field, over the environmental and source-induced noise component. The processing also geometrically rearranges the reflection energy of the wave field to produce an "image" or section of the subsurface, which is suitable for interpretation.

Presentation and interpretation: Using the final stacked section, and possibly intermediate processed seismic data, a physical model of the subsurface is developed. This model may represent structural, lithologic or stratigraphic geologic features.

These stages are normally not isolated and there is usually feedback (represented by the arrows above) from field processing into the acquisition parameters during the actual field acquisition. Also interpreted seismic sections may alter acquisition parameters used in further surveying in the same study area.

Survey design and acquisition of seismic data:

Geometry

One parameter that affects the quality or signal/noise ratio (S/N) of the seismic reflection data relating to a subsurface location is the number of seismic reflection raypaths that pass through that location from the source to receiver. The more reflected energy that is available to image the reflecting interface the better the definition, as long as the energy is not so large that inelastic deformation of the subsurface occurs. To increase the amount of subsurface locations that can be imaged in a unit of time the number of receivers or sources must be increased. It is normal to use a single source and multitude of receivers so that each source wavelet can be detected at many different surface locations and image many different subsurface points at once. By altering the location of the source and active receivers between shots, the subsurface can be imaged in a systematic way and several raypaths pass through the same subsurface location. This multiple imaging of the same subsurface location increases the S/N ratio and improves the quality of the stacked section. The multiplicity of raypaths passing through a single subsurface point is called "fold". If two raypaths pass though the same point then this is "two-fold", three raypaths "three-fold" and so on. The fold does not take into account the quality of the raypaths passing through the subsurface point. The desired reflection energy may be contaminated with ground-roll, air blast, refractions or environmental noise. This noise may have to be muted which therefore reduces the effective fold. To increase the fold and hopefully improve the quality of the final stacked sections several different surveying geometries have been designed. The four most common source-receiver geometries used in shallow seismic surveying are shown in Figure A6.1. Each has its own advantages and disadvantages.

End-on push spread (Figure A6.1a)

This spread geometry allows very shallow refractions/reflections and the direct wave to be recorded. This information can then be used to derive a near-surface velocity model and allow refraction statics to be applied. The disadvantage of the spread geometry is that receivers close to the source may be swamped with high energy ground roll, causing a reduction in the effective fold.

End-on push with offset (Figure A6.1b)

Using this spread geometry, shallow refractions and the direct wave energy may not be recorded, reducing the effectiveness of refraction statics without further supplementary information. The nearest geophone group is far enough away from the source so that it is not swamped by ground roll. This permits full fold coverage and the maximum source receiver offsets, therefore allowing better stacking velocity determination.

Split spread (Figure A6.1c)

In this configuration, the maximum source-receiver offset is decreased, reducing the optimum window and the accuracy of deeper stacking velocity determination. The advantage of the geometry is that the near surface data quality is improved as the effective shallow fold is increased. As for the end-on push spread, the nearest geophones may be swamped by high energy ground roll.

End-on pull (Figure 6.1d)

This spread geometry is geometrically identical, but reversed to, the End-on push spread (1a), and has the same advantages and disadvantages. It is important in land-streamer systems that are under development, where the source and land-streamer towing vehicle are usually the same, and are in front of the geophone array (van der Veen et al., 2001).

The fold (F) of a subsurface point (number of raypaths passing though that point) for the four geometries described is calculated by (Equation A6.1)

$$F = \frac{R}{2 * \Delta S / \Delta R} \qquad \text{Equation A6.1}$$

where R=number of receivers, ΔS=shot spacing, ΔR=receiver spacing. For example 48 active geophones with same geophone group and shot spacing will give 24 fold data. The signal to noise ratio of the stacked data can be calculated using (assuming that the noise is random) (Equation A6.2):

$$S / N_{ratio} = \sqrt{F} \qquad \text{Equation A6.2}$$

Therefore the fold (F) on a seismic profile, decreases in a non-linear manner with increasing $\Delta S/\Delta R$ ratio. This can be seen graphically in Figure A6.2. A four times increase in the shot spacing, with no increase in receiver spacing, will only decrease the S/N ratio by half. The S/N ratio of the survey is not, however, the only parameter in deciding the "fold" necessary to meet the requirements of the survey. The fold in many cases must also be high enough to allow stacking velocities to be determined and advanced processing algorithms may require higher fold and S/N ratio than simple imaging of subsurface features. Subsurface conditions in much of North Canterbury have required folds of > 6 for successful imaging and >24 fold if detailed semblance velocity analysis or more advanced seismic attribute analysis is undertaken.

The geometry of the survey used is, in general, such that the fold is high enough to meet the target of the survey while the number of shots and receivers is minimised, so that costs are reduced. From simple geometric considerations the fold of the survey line is not constant but varies at both ends of the line and hence the length of the seismic line undertaken must be longer than the feature being investigated. In general the line length (L) is calculated to be (Equation A6.3)

$$L = \Delta X + 2Z \qquad \text{Equation A6.3}$$

where ΔX is the lateral extent of the subsurface feature of interest and Z= depth of feature below the surface.

The line orientation is dependent on the goals of the survey but in many cases working parallel to the regional dip of the local strata usually yields the most useful data. The use of multiple lines to delineate the three dimensional subsurface form is also possible, but greatly increases acquisition costs. With presently available equipment and field costs true three dimensional shallow seismic is at present limited to research projects and geotechnical projects where non-invasive methods are necessary (Green et al., 1995; Bueker et al., 1998a, b; Bueker et al., 1998c). True three-dimensional acquisition requires the use of multiple seismic receiver lines that are being recorded at the same time as a single source is active. This requires a high channel (>98) seismic system to allow a realistic acquisition speed and results in complex field survey procedures. Three-dimensional, shallow seismic methods are likely to increase as equipment costs per channel decrease and less field intensive acquisition methods, such as multiple towed land-streamers, become more common (van der Veen et al., 2001). The use of two-dimensional seismic lines is therefore much more common and is usually improved by using a close array of 2D lines to simulate a three-dimensional seismic image (pseudo three-dimensional seismic) of the subsurface. True three-dimensional surveying and closely spaced two-dimensional surveys have several important advantages over simple two-dimensional lines:

- Small features near the lateral and vertical resolution limits of the survey, may be wrongly interpreted as “noise” in a single seismic line, but when seen in multiple lines, may be correctly interpreted as small but laterally or vertically continuous features. Many small faults can only be accurately defined when seen on several seismic lines.
- Unless non-seismic information is available to constrain the interpretation, even simple planar beds need to be imaged by at least two seismic profiles to define the true dips and strikes of the units.
- Many depositional and erosional features are defined by their three-dimensional geometry. Only by using multiple seismic lines is it possible to correctly distinguish between the different units.

- Noise such as out-of-plane reflections and diffractions, are processed on a single seismic line as though they are below the source-receiver. Three dimensional seismic profiles allow this noise to be identified and any interpretation modified.
- Three-dimensional surveying may allow quantitative estimates of subsurface volumes, complex fault displacements and isopach maps to be calculated. This can not be achieved with a single two dimensional line.

Optimum survey geometry

The optimum field acquisition geometry for a seismic reflection survey, must meet several key requirements:

- The near and far source-receiver offsets should be such that a good velocity model can be derived from normal move-out velocity analysis. Without a reasonable velocity model, depth conversion of the final stacked section will contain large errors, obviously reducing the usefulness of the survey.
- The receiver spacing must be such that spatial aliasing[1] is eliminated, so that spatially aliased data are not introduced into the final stacked section and wrongly interpreted as reflection events.

The minimum spatial sampling is calculated from (Equation A6.4) (Brouwer and Helbig, 1998):"

$$\nabla x = 1/k_{\min} \quad \text{where } k_{\min} = f_{\max}/v_{\min} \qquad \text{Equation A6.4}$$

and $f_{\max}$ is the maximum expected frequency and $v_{\min}$ is the lowest apparent velocity of waves , Δx is the spatial sampling interval and k_{min} wave number. Using average values, the minimum spatial sample spacing can be calculated (Equation A6.5):

$$f_{\max}= 100 \text{ Hz}, v_{\min}=1000 \text{ m/s}, x=2.5\ m \qquad \text{Equation A6.5}$$

- Topographic undulations should be at a minimum.
- Where more steeply dipping subsurface units are present the ray paths of the seismic reflection waves are both up and down dip. Steeply dipping events may have a very long reflection path. This may result in the need to have a longer spread length than would be anticipated, to image the structure correctly.

[1] Spatial aliasing is the introduction of artifacts due to the limited spatial sampling resolution.

- The near-surface velocity model, derived from the near-surface direct and refracted waves, must be accurately defined.

The optimum survey geometry is a source in the centre of a long receiver array with zero offset between the source and first receiver and very close receiver spacing. This optimum must be balanced by the equipment available, and by the field effort required for the survey. Based on a common target depth of 200 m through unconsolidated material (2000 m/s p-wave interval velocity) and using a 48 channel system, the receiver spread length would need to be 200 m maximum offset, with a receiver spacing of 2 m for optimum performance. Using a split-spread geometry and zero minimum offset the number of channels needed is 100. It can be seen from this calculation that the optimum survey geometry can only be used as a guide to survey design. To reduce the number of channels needed and retain a geometry which will allow for a successful survey, the following may be done:

- Change the acquisition geometry from split to off-end spread. This allows longer maximum source-receiver offsets with fewer receiver channels. However, it reduces the survey fold, and may not correctly image steeply dipping structures if the line is aligned incorrectly.
- Increase the receiver spacing. This will increase spatial aliasing, but careful processing may identify or reduce this, producing acceptable survey results.
- Increase the source-receiver minimum offset (X_{min}). In the majority of surveys the very near-surface reflection events are masked by large amplitude ground roll and trapped wave energy. This is often muted during processing removing any reflection energy. Increasing the source-receiver minimum offset means this reflection/ground roll energy is not recorded and only latter reflection events are available for further processing. The increased source-receiver offset also means that direct and early refraction energies are not recorded and very near-surface refraction/direct wave velocity calculation is impossible. This reduces the effectiveness of processing methods such as refraction statics, and leads to errors in the very near-surface velocity model, which are then incorporated into the overall final stacked section velocity/depth model.
- Use multiple sources to simulate a larger array or different array geometry.

The X_{min} near offset is usually calculated from test shot field records (Figure A6.4), derived from modelling or assumed from previous surveys in similar subsurface conditions. X_{max} normal moveout should be sufficient to accurately determine subsurface velocities, but not too large to introduce normal moveout stretch. Reducing the X_{max} reduces accuracy of velocity determination and hence depth conversion, but X_{max} must be much less than the depth to the reflector for the small-spread approximation to be valid (offset small compared to depth) (Equation A6.6) (Yilmaz and Doherty, 1987).

Small-spread approximation

$$t^2_{(x)} = t^2_{(0)} + \frac{x^2}{v^2_{rms}} \qquad \text{Equation A6.6}$$

where $t_{(x)}$ is the travel time to receiver at position x, $t_{(0)}$ is the vertical incidence travel time, and v_{rms} is the root mean square velocity down to the reflector.

Measurement of actual field geometry

There is often a difference between the calculated theoretical geometry and actual field geometry used. Geophone and source spacing may be accurately defined using a tape measure, but absolute errors in the position of sources and receivers quickly develop due to tape stretch, poor alignment of tape ends, misread tape positions and other procedural errors. It may also be necessary to move geophone and source positions from those calculated, due to unexpected immoveable objects (fences, streams etc) occupying calculated geophone/source locations. The topographic surface is also usually undefined pre-survey and so is measured once source-receiver positions have been established. The positions are surveyed using a theodolite or differential satellite Global Positioning System (GPS). With GPS equipment the measurements are usually phase-code corrected and have an RMS error of 0.2 m in the horizontal and 0.4 m in the vertical for an instantaneous (1 s) position fix. GPS surveying requires ≥ 4 good satellite locks for an accurate geographic fix, and for phase code sub-metre correction >10 minutes uninterrupted phase logging. This can result in difficulty obtaining a good position fix under tree canopy, in steep sided valleys and other areas where many seismic surveys are undertaken. It may be necessary to obtain positional fixes along the line when possible, and then fill-in the line with conventional surveying techniques or interpolation of the available surveyed topography. For surveys where less accurate topographic and lateral positions are required p-code differential GPS surveying has cost and time advantages as it requires longer individual point position fix acquisition time (<45 s) but no minimum total logging interval. This means a position can be obtained immediately after lock with a satellite is lost and reestablished with no ten minute wait. For seismic lines with poor or patchy sky visibility the need to re-establish a ten minute lock can result in dramatically increased surveying times.

Receiver elements (Geophones)

The choice of the receiver element, the geophone, is usually controlled by what is available and not what is optimum. Geophones come in many different frequencies from 4 Hz-100 Hz, and usually have a useful bandwidth of ten times their natural frequency, before phase distortion becomes a problem (Steeples and Miller, 1991). The sensitivity of the geophone is dependent on several factors:

- The inherent sensitivity (manufacturer dependent).
- The electrical damping of the frequency response (to reduce the effect of a peak in the response at the element's natural frequency).
- The orientation of the geophone element. The element is most sensitive when orientated in the vertical direction when compared with the earth's gravitational field (operator controlled).
- The mechanical springs used in the construction of the geophone element tend to deform with time and use and micro-cracks form, which reduces the geophone's sensitivity over time and changes the geophone's phase response.
- The coupling of the geophone with the subsurface. To increase the coupling, a spike is often used to penetrate the unconsolidated soil layer and contact with the more consolidated zone several cms below the surface. Depending on the environment the use of shorter or longer spikes may be necessary. A novel screw-in geophone was also tested during this thesis (Appendix 3).
- The electrical summing of individual geophone signals, to produce an equivalent pseudo geophone, can be accomplished by placing several geophone elements in close proximity and wiring the signal in series. This in effect increases the sensitivity as the geophones are receiving the same in-phase signal from the subsurface. If the geophone array elements are spaced apart the array will have a complex frequency and directional sensitivity function, but with small geophone array spacing most effects are at frequencies above practical surveying frequencies. For a simple three geophone array with 2 m spacing, notch frequencies in the response occur at >300 Hz for average subsurface conditions (Pritchett, 1990).

Sources

To image the subsurface in detail, a seismic source must have several key characteristics. It must be powerful enough to penetrate the subsurface to the depths of interest and return a reflection wavelet with enough energy that it can be detected above environmental and background noise. It must also have high enough frequency bandwidth, so that the subsurface is imaged to the required detail. Any source must also be reliable, portable, and cost effective. To meet these requirements, many innovative and diverse sources have been constructed and tested. Surveying in Canterbury has been undertaken using three commonly used sources: i) hammer and plate ii) seismic pipe gun iii) mini-Sosie ™.

Figure A6.5 and A6.6 show the frequency content of shot gathers for shallow targets using these different sources. Figures A6.5c and A6.5d show that the seismic pipe gun has a higher frequency content between 100-200 Hz than the hammer and plate source and Figures A6.6c and A6.6d show that the hammer and plate has a higher bandwidth than the mini-Sosie ™ source.

Hammer and plate

This a simple and cost effect source and is widely used in shallow seismic surveying. The hammer has a simple mechanical or piezo-electric trigger attached, which allows the impact on the plate to be detected. The hammer can vary in size depending on the user and usually gives several thousand impacts before maintenance is necessary. The plate can be either steel or aluminum, and can last up to 5000 hits before metal fatigue failure. The individual impacts from the hammer impart only a small amount of seismic energy into the subsurface ($\approx$ 50 J per impact) but repeated stacking of the data increases the signal strength while decreasing the random noise component by the square root of the number of stacks (Equation A6.7).

$$S/N = \sqrt{\text{stacks}} \qquad \text{Equation A6.7}$$

The effort or energy required to achieve an increase in S/N ratio, increases linearly with the number of stacks (total energy of each impact times the number of impacts). The S/N ratio increases with the square root of the number of stacks. As can be seen from Figure A6.7, the optimum signal-to-effort occurs for four stacks. This optimum may have to be increased for deeper reflectors or noisy seismic environments. Good mechanical coupling of a hammer seismic source with the subsurface increases both the frequency range of transmitted seismic energy and the magnitude of the transmitted energy. The aim is to transfer as much kinetic energy from the moving hammer into the plate and then through the plate into the ground. The choice of material for the plate affects this transmission, but the shape and mass of the plate appears to only affect the transmission to a minor extent (Keiswetter and Steeples, 1995). The choice of plate is affected mainly by the mechanical constraints imposed upon it. The use of ship steel at least 2 cm thick and of circular shape (0.3 m in diameter), results in a plate which is easily transported by a single person and is able to survive several thousand impacts. To increase coupling to the ground and reduce any bouncing of the plate several methods may be applied. The plate can be placed in a tight fitting, flat-bottomed hole below the highly absorbent, very near surface material. This constrains the plate and increases coupling, but requires holes being dug at each shot location which reduces survey speed. Where soils and near surface materials are compacted at the surface, such as along metalled roads, the plate may be placed directly on the surface. The plate is then held down during the hammer impact, by pressure being applied to a chain attached to the side of the plate. This method improves acquisition rates but is dependent on using an experienced and accurate hammer operator for safety reasons.

Triggering

Improvements in the S/N ratio of stacked seismic data requires that the triggering for each stacked record or shot be accurately defined. Incorrect timing will result in out of phase stacking of data and reduce the high frequency component of the stacked wave field and a reduction in the expected S/N ratio. Three options are used for triggering the seismograph when the hammer impacts the plate:

1. A mechanical trigger mounted on the hammer near the hammer head. This method is relatively reliable when using a sealed, impact sensor. However, the mechanical fitting which holds the sensor and cable on to the handle of the hammer can fail after several thousand impacts due to the large deceleration forces.
2. A geophone located next to the plate to detect the impact through the ground. This method tends to introduce a small delay (<1-2 ms) due to the travel time from the impact point to the geophone and geophone response time. It is a very reliable method, as the geophone does not experience the dramatic forces experienced by a sensor mounted directly on the hammer. The disadvantage is the geophone has to be coupled to the ground near the plate, which takes time and slows the survey down.
3. Use of electrical contact between the plate and hammer. A cable is connected to the hammer head and plate. The connection to the plate is usually done using a large crocodile clip and the hammer has a connection directly to the head. The timing is accurate to <1 ms,

but mechanical failure of the cables or connectors is common, and wet conditions may cause false triggering on the seismograph. This method was also found to induce electrical noise in several surveys, probably caused by the interaction of electrical ground loops between the grounded plate and geophones and impact generated, electro-seismic noise. The noise appears to occur during the bounce of the plate after impact (0.2 s), and appears to be greatest when the ground is damp.

Seismic pipe gun

The seismic pipe gun is a simple and cost effective source, but has several operational disadvantages (Pullan et al., 1987). First, it requires two operators to drill the holes for the source. Second reloading of the gun is slow (≈1 minute) due to the need to keep the mechanism clean from contamination to reduce misfires. The source is inherently dangerous and therefore requires constant operator attention. Its advantages are that it can be placed below the water table, can give very good coupling with the subsurface, and has a high amplitude, large band width, impulsive signal. Due to the down hole operation of the source, the ground-roll is usually reduced compared to surface sources. In the North Canterbury sediments a 200-300 % reduction in maximum amplitude of the ground-roll is usually seen between the pipe gun source and the hammer and plate source. Triggering of the pipe gun is usually achieved by mounting an over-damped geophone on the outside of the pipe near the blank cartridge, with trigger accuracy of less than 1 ms.

Mini-Sosie ™ (Earth Compactors)

The mini-Sosie ™ source was devised by Barbier (1977) as an alternative to Vibroseis and explosive methods (these methods not discussed in this thesis) for shallow (<1 km) targets. It was designed to send a high frequency signal into the ground using commonly available civil engineering earth tampers, alleviating the need for sophisticated and expensive equipment (Barbier, 1977).

The method uses a sequence of pseudo-random impacts to simulate a single large impact, or zero-phase wavelet. The energy of the individual impacts is additive and so the source signature represents a very high amplitude signal with very good penetration. The mini-Sosie ™ method works by correlating the source signal against the received geophone signal. The cross correlation of these two signals gives an instantaneous, shot-gather, wave field. The source signature is of lower frequency than the pipe and hammer sources, but can penetrate to a greater depth. The limitation of the mini-Sosie ™ source is its slow acquisition time (several minutes with a minimum of two earth compactors), which is necessary to generate the pseudo-random sequence. Also a large number of field personnel are needed for the operation of the source. The equipment is mechanically difficult to maintain and has a high maintance and financial overhead. A simplified diagram of the mini-Sosie ™ system and earth rammer impact sensors is shown in A6. 8 and A6.9. The theory underlying the mini-Sosie ™ method is described below:

Theory of coded impact seismic technique
based on the work of Barbier (1982) and Park (1996).

A single source pulse seismic record $r_s(t)$ can be expressed as the convolution:

$$r_s(t) = s(t) * e(t) + n(t)$$

where $s(t)$ represents the source single seismic pulse, $e(t)$ the earth response and $n(t)$ the ambient random noise component. In mini-Sosie ™ the source s(t) pulse is replaced by a series of impulses occurring over a set time interval. This can be represented as a sequence $\psi(t)$ of a single impulse convolved with a sequence of zeros and ones.

$$\psi(t) = y(t) * s(t)$$

where $y(t)$ = impact sequence 0,0,0,0,1,0,0,1,0,1 etc and $s(t)$ is a single seismic impulse. The single source pulse seismic record $r_s(t)$ can then be expressed as

$$\begin{aligned} r_c(t) &= \psi(t) * e(t) + n(t) \\ &= y(t) * s(t) * e(t) + n(t) \end{aligned}$$

To obtain $rc(t)$ as a conventional single impulse response shot gather record $r_d(t)$ the impact sequence y(t) must be cross-correlated with the recorded impact sequence.

$$\begin{aligned} r_d(t) &= y(t) \oplus r_c(t) \\ &= y(t) \oplus [\, y(t) * s(t) * e(t) + n(t) \,] \\ &= \mathrm{ACF}[\, y(t) \,] * s(t) * e(t) + y(t) \oplus n(t) \end{aligned}$$

conversion of this equation into the frequency domain allows an easy interpretation of the effects.

$$|P_d(j\omega)| = |Y(j\omega)|^2 \times |S(j\omega)| \times |E(j\omega)| + |Y(j\omega)| \times |N(j\omega)|$$

Ambient Noise

The signal $S(j\omega)$ is multiplied by the power spectrum of the coded signal $Y(j\omega)$ while the ambient noise $N(j\omega)$ is multiplied by the square root of the power spectrum. Hence as the length of the coded sequence increases the S/N ratio also increases with the square root of the number of impacts. For mini-Sosie ™, the signal to ambient noise ratio reaches an acceptable level after several hundred impacts, but the signal may still be swamped by correlation noise until several thousand impacts.

Correlation noise

The autocorrelation of an infinitely long totally random sequence $\psi(t)$ of 0s and 1s is a single peak and would represent a perfect zero phase wavelet of infinitely short duration. Therefore the cross correlation of $\psi(t)$ and the coded seismic record $r_c(t)$ would be the decoded seismic record $r_d(t)$ with only random environmental noise and no correlation noise. In actual use the mini-Sosie ™ impact sequence is of fixed duration and is not random. The time interval between impacts is to a large extent controlled by the earth rammers mechanical properties and the operators can only alter the impact rate over a small range (1-12 impacts/s). The number of impacts is also limited due to the constraints of the survey. To improve the randomness of the impact sequence several rammers may be used but in general the impact sequence frequency rate is usually a Gaussian-like distribution centered on the normal operating rate of the earth rammer. From standard time series analysis the correlation background for a pseudo-random impact sequence will consist of successive correlation peaks centered at time nt_0 where n is an integer *(1,2,3 ....)* and t_0 is the mean time between impacts. The amplitude of the peaks in the correlation background will be given by the following equation:

$$An = \frac{1}{\sqrt{2\pi\sigma\sqrt{n}}}$$

where σ is the standard deviation.

The correlation background is unwanted and must be reduced. This may be achieved by increasing the randomness of the impact sequence and so increasing the standard deviation. This will decrease the amplitude of the correlation background peaks at (nt_0) and hence reduce the overall correlation background noise.

In summary

The frequency of the equivalent mini-Sosie seismic source wavelet is dependent on the rate at which the momentum of the rammer impact plate is transferred to the ground. The compaction of the subsurface, the weight of the rammer and the velocity of the rammer plate all control the frequency of the source wavelet and not the mini-Sosie ™ correlation process. The signal to noise ratio between the post correlated source wavelet signal and the random background noise is $S/N = \sqrt{N}$ where N is the total number of impacts. The correlation background noise is related to the standard deviation of the Gaussian distribution of impact intervals. From field experience it is known that the number of impacts necessary to image a reflector is controlled by the need to reduce the correlation background level and not the random environmental noise to signal ratio. Less than several hundred impacts is usually sufficient to obtain a signal to environment noise level ratio that allows reflectors to be determined but several thousand impacts are usually necessary to randomness the impact sequence enough to reduce correlation noise to a level acceptable for reflection surveying.

Average costs per shot point

The controlling factors in acquisition rates are expediency of geophone and cable placement and the shooting rate. The geophone placement rate can be increased by several methods:

- Selecting easy-planting conditions, such as next to roads and tracks. The profile line should be selected where there are as few obstacles as possible (obstacles include fences, hedges, streams, stock, crops etc). Seismic line acquisition rates across difficult terrain are often only 50% of that achieved on more open terrain.

- Using fewer geophones (per geophone group). This, however, reduces the group sensitivity and requires multiple geophone sets.

Shooting rates can be increased by increasing shot interval (reduces fold), reducing the number of stacks for a hammer and plate survey or reducing the overall recording time for mini-Sosie ™ source. A reduction in any of these parameters also reduces the data quality and penetration, and so a balance must be selected between acquisition rates and survey aims.

Table 1 shows the average likely cost per shot point for three different sources. The number of shot points achievable is variable depending on amongst other things, surface and subsurface conditions, weather, field crew ability, mechanical failures. The values used are an estimate from field experience of a "normal" field day, utilizing two field crew. All costs are in 2003 New Zealand dollars.

Table A6.1: Average cost per shot point for three different soures

Source	Shots/day	Expendables/day	Cost/shot	Notes
Hammer and plate	200	None	$1.2	Eight stacks at each location
Mini-Sosie™	100	Fuel $20	$2.6	Two earth compactors, each 1000 impacts/shot point
Seismic Pipe Gun	120	Fuel $20 Blank cartridges $1 each	$3.2	Drilling and shooting holes. Four minutes per hole including drilling, shooting, refilling hole.

Noise

Natural and cultural environmental noise reduces the quality of all seismic data collected. This noise can derive from many sources but several important ones commonly encountered are listed below:

Cultural Noise

Traffic: Cars and trucks on nearby roads produce very strong ground roll which swamps any reflection signal. Large trucks produce a signal which swamps reflections at distances of less than 2 km, cars within 1 km. The source used has a large influence on whether a survey is practical near traffic noise. Mini-Sosie ™. is the least effected, followed by a multiple stack, hammer and plate survey and the most affected is a seismic pipe gun survey, which is usually swamped by any traffic noise.

Aircraft: Any aircraft noise swamps the seismic signal with very powerful low frequency noise. Surveying is impossible using hammer and plate or seismic gun source when aircraft noise is present.

Electric fences: These introduce a large spike into the seismic data by electromagnetic inductance. The spike is of very short duration (< 10 ms) and usually occurs every 1-2s. Due to its repetitive nature, the effect rapidly degrades the quality of stacked hammer and plate and mini-Sosie ™ surveys. In most cases the effect is removed by post acquisition muting of the effected records or by simply turning off of electric fences where possible. Shallow seismic gun surveys may not be greatly affected as they are not usually stacked, and so may not record the induced electric fence noise during the important 0-300 ms time interval after each shot.

Utilities: Underground and above ground utilities have a large effect on the seismic data quality. High voltage buried cables induce very strong 50 Hz and higher harmonic interference which swamps any reflection signal. If possible seismic cables should not be laid directly above or below high voltage cables. Noise from water pipes also reduces data quality and should be avoided, but is usually only a problem when water is flowing in the pipe.

Pumps: Water pumps (electrical, diesel and petrol powered) produce strong acoustic seismic frequency noise. This noise, which is well coupled to the subsurface will swamp any seismic signal up to several hundred metres away.

Farming/agriculture: Stock movements cause a huge amount of seismic noise and will swamp any reflection signal when large numbers of animals are moving. As a group normal grazing patterns of sheep, deer or cattle will usually allow seismic surveying to be undertaken outside of a 30m radius from any animals without significant interference.

Natural Noise

Stream and Rivers: Waterways, including streams, produce strong low frequency noise which greatly reduces data quality. The affected radius is dependent on the waterway size, but even small streams can swamp the reflection signal within ten's of metres from the channel.

Trees: Even in moderate wind speeds moving/swaying vegetation of any sort produces a large amount of seismic frequency noise. The effect is believed to be caused by movement of the plant's root ball. Areas with large trees and high grass and crops should be avoided if possible.

Wind: Seismic data quality is highly dependent on wind speed, and plant growth near the geophones. No successful shallow seismic survey has been obtained in North Canterbury during greater than 20 knot winds, without burying geophones or removing grass and vegetation near the geophones.

Rain: A single raindrop will swamp a geophone and those nearby for greater than 100 ms after impact. Data collection in full rain is therefore impossible. Data collection can be undertaken in light rain with a corresponding reduction in data quality, but electrical interference may cause further problems due to geophone/cable earthing loops. Therefore surveys on calm, clear days present the best conditions for good results.

Marine Waves/ Beach Surf: Beaches tend to have a high ambient background noise level from waves breaking on to the beach, but several successful surveys have been completed using stacked impact sources e.g. Pines Beach survey in this thesis. It appears that a majority of the seismic noise is low frequency and can be removed using a simple low cut filter.

Processing:

The basic concepts of shallow seismic reflection surveying are relatively simple, but the processing and interpretation can be quite involved. This is due to the inclusion of coherent and random noise, within the seismic data, that must be removed or reduced to allow the reflection data to be highlighted.

The processing of seismic reflection data is based on several assumptions (Anderson, 2000):

1. Seismic velocity is a function of density and elastic moduli. The acoustic impedance is the product of velocity and density. The Earth consists of layers of effectively uniform acoustic impedance.
2. There are only two fundamental types of body waves that propagate, P-waves (compressional) and S-waves (shear).
3. In homogenous media energy propagates from a surface source as a hemispherical front (7% P-waves, 67% Rayleigh, 26% SV-waves (Lamb, 1917).
4. The velocity of S-waves and P-waves is a function of the properties of the material and can range from <200m/s – 8500m/s for P-waves (v_p) (Equation A6.8) and less for S-waves (v_s) ($v_p \geq 1.15v_s$) (Equation A6.9) (Brouwer and Helbig, 1998).

   $$v_p = \sqrt{\frac{(K+4\mu)/3}{d}} \quad \text{Equation A6.8} \qquad v_s = \sqrt{\frac{\mu}{d}} \quad \text{Equation A6.9}$$

   where d is the sediment/rock density, μ is the shear modulus and K is the bulk modulus.
5. A seismic wavelet can be characterised by its frequency, amplitude, wavelength and phase.

6. Energy incident on an acoustic impedance boundary, will be reflected and refracted in accordance with Snell's Law. The mode of the incident wave may be converted at the boundary.
7. The amplitudes of the transmitted and reflected wavelets can be calculated using Zoeppritz equations.
8. On stacked seismic sections, the raypaths are assumed to be normal to the interfaces and the individual traces are the sum of multiple ray paths with the same point of reflection in the subsurface.
9. Migrated seismic data has had the effect of the non vertical raypath removed, so that the seismic section has boundaries correctly located and diffractors reduced to point sources.

Seismic reflection field data contain individual shot records corresponding to either a single shot or multiple shots recorded with the same geometry (stacked). The location of the source and receivers are recorded but the shot gather is not interpretable from these raw shot gather records as they include the unwanted noise, the effect of the differing source-receiver geometry and poor velocity information. The aim of reflection processing, is to extract the information relating to the lateral and vertical geometry of the reflection boundaries from within the shot gathers and obtain an interpretable subsurface image with the acoustic boundaries in their correct geometric position and depth. A detailed explanation of seismic reflection processing is beyond the scope of this Appendix, but can be found in several texts (Yilmaz and Doherty, 1987; Steeples and Miller, 1991; Reynolds, 1997). The key shallow seismic processing stages are:-

Conversion

Re-sampling

Geometry

Bad Trace Removal

Frequency Filtering

F-K Filtering*

Gain

Deconvolution*

Field Static Corrections

Muting

CMP[2] Sorting

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[2] CMP is the abbreviation for Common Mid Point and is used interchangeably with CDP Common Depth Point by many authors, but this is only correct for planar horizontal reflectors.

Velocity Analysis

NMO

Residual Statics

Stacking

*Migration**

*Depth Conversion**

Where * indicates an optional processing stage, which is often found not to improve the coherency of the final stacked section in shallow seismic sections.

Processing requires the recorded seismic data to have a high enough sampling rate so that the data is not frequency alaised, that the record length is large enough that all reflectors are recorded, and accurate trigger timing so that the individual shot gather data sets can be correctly combined. To correctly process seismic data, the three-dimensional geometry of each receiver and source for every shot is also needed. Without this information, the conversion of the shot gathers from the shot gather domain into the CMP domain, is not possible. The geometry may be applied directly into the field header of the seismic data or during the later processing stage. [Geometry for all seismic data in this thesis was obtained using differential GPS or when topography was minimal, simply measured distances along the profile, without height information].

Processing Software used

Several seismic processing software packages were used during this research. Initial processing was undertaken using the Kansas Geological Survey WinSeis© package (KGS, 1996). This proved to be very limited in its application and all subsequent processing used the Colorado School of Mines Seismic Unix package© (Stockwell, 2000). This was successfully used, but a commercial PC Windows operating system front end (Visual Sunt©) was purchased to increase the speed of processing (Jacques, 2003).

Conversion

Shallow field seismic data are usually collected in SEG-2 format. This format is an updated version of the earlier SEG-Y format and is designed to take advantage of new features of digital seismographs. One of the main differences in the format is the recording of individual shot records as separate files and not as a continuous record, as in SEG-Y format. The raw SEG-2 data are then converted into a format that can be handled by the processing software being used. For North Canterbury data, the processing data software (Visual Sunt) uses the seismic Unix format (SU) (Jacques, 2003).

Resampling

Field data are normally collected at the highest sampling rate that is available, with a record length that is considerably longer than it is anticipated will be needed. This generates large files, but guarantees that no available information is lost during acquisition, which is expensive in time and money. To increase processing speeds and reduce storage requirements, the raw data is re-sampled using more conservative parameters. Incorrect application of re-sampling can induce high frequency noise into the seismic section and result in the loss of detail. Modern processing software and hardware can easily now handle 100 Mb data files and undertake most processing functions in near real-time so the need for careful reduction in sampling frequency is less stringent than was previously required. For most near-surface work in Canterbury, the expected frequencies are <500 Hz giving a Nyquist frequency of 1000 Hz. In most cases a very conservative sampling frequency of 2000 Hz has been used.

Geometry

If the receiver-source geometry has not been applied in the field, this information is added at this stage. The field files are also renamed so that they are consecutive and any bad files are removed. The application of the correct geometry is vital for shallow surveying. The features being imaged are often laterally and vertically small and discontinuous. Small geometry errors such as incorrectly missing a shot location, introduce processing artefacts that are very similar to real subsurface features. The geometry is also carefully checked against detailed field logs and self consistent checks made, such as:

- Are the total number of shots being processed equal to the field records ?
- Is the airwave velocity $\approx$ 330m/s ?
- Are dead traces where they are expected ?
- Are adjacent shot gathers similar ? Dramatic changes in reflector, refractor or air-blast shape are unlikely in the raw shot gathers as they are sampling nearly the same subsurface locations, but lateral changes in the very near surface material may induce rapid amplitude variations due to changes in source coupling.

- Are shot locations the same as recorded in the field ? A useful method to check geometry is the alignment of the expected source location with the direct wave and airwave on the raw shot gathers. Incorrectly applied geometry will result in a misalignment of the source location and apex of the noise cone (Figure A6.3).

Bad trace removal

Bad traces on a seismic line are corrected, whenever possible, before shooting. However, most surveys contain some traces which contain very little or no useable data. If they are not removed these traces will reduce the quality of the final stacked section. The bad traces can be the result of a sticking geophone, a bad connector, poorly planted geophone, or utility cables beneath a geophone location. Trace removal is usually undertaken manually by inspection of each trace in a shot gather. Bad trace removal is subjective, and can be affected by the aims of the survey. A trace which has a similar signal to its neighbouring traces, but reduced amplitude, may be kept when a survey has relatively low fold. This may allow the lateral continuity of the stacked seismic section to be kept. The same trace may need to be removed on a real amplitude survey, where its poor coupling or sensitivity would induce a spurious signal. Reversed traces due to reversed geophone connections can be easily identified by visually inspecting the shot gather. These traces can then be inverted during processing.

Deconvolution

Deconvolution of the seismic data aims to improve the temporal resolution of the data by compressing the basic seismic wavelet (Yilmaz and Doherty, 1987). Two secondary effects are the removal of some of the multiple energy and a reduction in reverberatory character of the seismic wave field. Deconvolution of non-shallow reflection data is successful at achieving this, but deconvolution of shallow seismic data has not been as successful. The theoretical basis of deconvolution is that the subsurface consists of many acoustic boundaries. This is normally violated for shallow seismic reflection surveys where usually <<10 subsurface boundaries are imaged. The use of deconvolution to remove or reduce reverbatory signals from the wave field can also cause problems in shallow seismic. Many of the subsurface features that are to be imaged are of cyclic sedimentary origin and may have a cyclic period of the same magnitude as any reverbatory signal. Deconvolution if incorrectly applied may have the effect of removing the signal of interest. In North Canterbury pre- and post-stack deconvolution of the seismic wave field has, in general, resulted in reduced image quality or removal of features which may be of real sedimentary origin and therefore of interest. The use of deconvolution should be approached carefully and evaluated for each seismic survey.

Frequency filtering

Frequency filtering is a simple method of enhancing the reflection component of the acoustic wavefield, while reducing the effect of unwanted, coherent, source-generated noise and some environmental noise. In shallow seismic data the dominant reflection component of the wavefield may be a magnitude higher than the ground-roll component. The correct application of a low cut filter can therefore enhance the reflection data. The high frequency content of the wavefield often contains air-coupled noise, which is reduced by the correct application of a high pass filter. Careful and detailed selection of the optimum frequency filters using parameter testing while the data are in the shot domain, can greatly improve the final processed stack section.

Gain

Spherical divergence, attenuation and differing receiver-source geometry causes a decrease in signal amplitude with travel time. This reduction in signal strength must be compensated for, if deeper reflection events are to be imaged. There are many different methods for compensating for the reduction in signal strength depending on the interpretation that will be applied to the final sections. If real amplitude information is needed then a model of the attenuation with time must be applied. For most shallow seismic surveys a simple automatic gain control (AGC) is applied. The values used for the AGC window is usually determined by parameter testing, but for all shallow surveys undertaken in North Canterbury an AGC window between 20 – 100 ms has been found to be appropriate.

Field static corrections

Field static corrections attempt to remove the effect of relative changes in elevation and lateral changes in the weathered layer, from the final stacked section. First, the (relative) geometry of the line must be accurately defined. Also the velocity of the weathered zone within the subsurface must be known. The subsurface velocity of the weathered layer can not be derived from reflection NMO as it is almost certainly within the noise cone. Either direct subsurface-surface shots can be used or the refraction component of the seismic wave field used. A seismic reflection survey usually has a multitude of source-receiver refraction paths. Using this information, a detailed near-surface velocity model can be obtained. Elevation corrections are not always necessary when processing seismic data. A planar surface with a small dip can be processed as a horizontal section and the final stacked section rotated to the dip angle of the section surface. The mathematical theory underlying seismic reflection is the same no matter what the dip of the section surface. The static corrections necessary for small elevation changes along a line (<1m) are usually on the order of 0-5ms and represent a wavelength of one quarter to 2-3 times a single seismic wavelet. If the topographic and lateral velocity changes are very rapid, this results in major destructive and constructive interference of the received wavelet, from the CMP stacked raypaths. This has the effect of reducing the coherence of the stacked section and the signal-to-noise ratio. Topographic features and lateral velocity changes that are unprocessed, result in the generation of non-reflection artefacts superimposed on the seismic section. Many small scale, topographic surface features are non-random in nature and may result in adjacent shot and receiver positions having only minor topographic differences. This difference may be gradual and result in only minor reduction in the quality of the CMP stacked data. The overall topographic feature will be superimposed in the stacked section, but the reflector character may not be reduced in quality. In many areas of North Canterbury, it is usually not necessary to define the surface topography to better than one metre, as very little improvement in data quality is obtained.

Muting

Noise Cone

The muting of noise within the shot or CMP gathers is dependent on the aims of the survey. For very shallow surveys (<50 m) it may be desirable to retain all information within the shot noise cone, and use frequency and F-K[3] filtering techniques to separate the noise and reflection wave field data. For deeper surveys, the noise cone may reduce the data quality of the final stacked section dramatically if it is not removed. Processing of the section with *and without* the noise cone muted, is usually the best way to decide if any useful data can be extracted from the noise cone.

Refractions

[3] F-K filtering refers to filtering in the frequency-wavenumber domain on time and space variant variables.

The refraction wave is usually removed during processing. A preliminary stack which includes the refraction data allows the effect of this data on the final reflection data to be quantified. If the survey target is outside of the refraction stacked zone, it is possible to use the unmuted shot gathers and eliminate the effect of refraction energy in interpretation. The determination of the refraction component and any associated trapped wave energy wave-train from early reflection energy, can be extremely difficult. Several key points are used to decide if the energy is refraction or reflection:

1. A refraction is travelling for part of its travel time in a faster layer and so has a higher apparent velocity than the reflection from the same interface.
2. A raypath has a minimum critical angle before which a refraction is impossible.
3. Refractions tend to have a similar frequency to any underlying reflections on a shot gather and slightly higher frequency than underlying reflections in the stacked section due to NMO stretch.
4. Refractions are usually larger magnitude than reflections.
5. Refractions are never crossed by reflections.

F-K filtering

Most processing occurs in the *(x,t)* domain. The *x* represents some relative position dependent on the geometry (shot gather, CMP gather, stack) and *t* represents an increasing time down each trace. The shot domain can then be thought of as representing a sub set of the *(x,t)* domain where x is the source-receiver offset. *F-K* filtering involves the conversion from the *(x,t)* domain into the *F-K* domain, where *F* is frequency and *K* is wave number. In the *F-K* domain reflection energy will have a different apparent dip than coherent noise events such as ground-roll, refractions and air-blast. This coherent noise energy can then be removed using *F-K* muting and so increase the reflection to noise signal ratio. A major problem with the application of the method to shallow seismic is the overlap of refraction and reflection energy in the *F-K* domain. Refraction energy tends to have similar frequency and wave number to reflection energy, and so is difficult to separate without destroying or reducing the reflection component. The removal of the slower phase velocity ground-roll and air-blast has been found to be more successful as the separation in the *F-K* domain between the coherent noise and reflections is usually larger. Due to the effectiveness of *F-K* filtering, careful control of the filtering characteristics is vital if artefacts are not to be introduced into the filtered data. A strong *F-K* filter can induce horizontal artefacts in the *(x-t)* domain data that are not real. As reflection energy within the noise cone is usually not visible at early two way times, it is not possible in many cases to know if after *F-K* filtering, apparent reflection energy is real or an artefact. For this reason it is often found more advantageous to mute out the noise cone completely and not attempt to recover any early reflection energy within the noise cone. After *F-K* filtering the data is transformed back into the *(x,t)* domain. (A fuller discussion of *F-K* filtering for hydrocarbon exploration depth seismic can be found in (Yilmaz and Doherty, 1987).

Common mid-point sorting

All processing up to this stage has been undertaken (except *F-K* filtering if applied) in the *(x,t)* shot gather domain. To increase the fold for each subsurface location the data is now resorted into common mid point (CMP) gathers ((*x,t)* CMP gather domain). Each CMP gather represents a set of seismic reflection raypaths from source to receiver (from all available) that have a common mid-point.

Note: Common mid point (CMP) and common depth point (CDP) are often used interchangeably but are only equivalent when the reflectors are horizontal and velocities do not vary laterally (Yilmaz and Doherty, 1987). Where possible the term CMP is used throughout this thesis.

Velocity analysis

A key stage in shallow seismic processing is the derivation of the lateral and vertical velocity model. The successful application of the NMO correction, migration and depth conversion, is dependent on this stage. The process is usually an iterative process and may involve repeated attempts to derive a more realistic and detailed velocity model. The derivation of an accurate velocity model is affected by many parameters in both the acquisition geometry and processing stage (Yilmaz and Doherty, 1987), including:

1. spread length
2. stacking fold
3. signal/noise ratio
4. muting
5. time gate length
6. velocity sampling
7. choice of coherency measure
8. true departures from hyperbolic normal move-out; and
9. bandwidth of data.

Care should be taken when deriving the acquisition parameters for a survey so that the calculated velocity errors are less than the requirements of the survey e.g. if depths are required to +/- 5% error the survey and processing parameters will need to be carefully chosen. In shallow seismic the most common velocity analysis methods are:

i) The velocity scan

The velocity scan uses a numerically intensive method to produce a stacked section for a range of velocities. The velocity range is usually chosen to be +/-1000 m/s above and below the expected velocity range. The stacking velocity model used is a single-valued model with no lateral or vertical change. The velocity steps for each of the constant velocity stacks is initially chosen to be large (200 m/s) and then reduced once the bounds for stacking velocities are found. For example a typical range of stacking velocities would begin with 1000m/s, 1200m/s, 1400m/s, 1600m/s, 1800m/s, 2000m/s, 2200 m/s, 2400 m/s, 2600 m/s, 2800 m/s, 3000 m/s and then be reduced to 1400m/s, 1450m/s, 1500 m/s, 1550 ms, 1600 m/s, 1650 m/s, 1700 m/s, 1750 m/s, 1800 m/s, 1850 m/s once the stacking velocity for coherent stacking has been identified. The stacking velocity is chosen by selecting the part of the stacked section that displays the most coherency at each velocity. This selection is subjective, and usually involves a relatively simple velocity model with a linear velocity increase with depth. Lateral changes in velocity, or dipping events, may be identified by changes in the coherency of reflection packages. If the apparent change in velocity of dipping events is not accounted for it may result in incorrect true stacking velocities.

ii) The constant velocity stack

This method is similar to method i) above, but only a limited subset of CMP locations along the seismic profile are used for each constant velocity stack. This allows any lateral velocity changes to be determined.

iii) Semblance analysis

Semblance analysis allows a statistical estimation of the coherency of CMP domain reflection events for varying NMO velocities to be calculated. The optimum NMO velocity can then be picked for each reflection event at each CMP location and a detailed lateral and vertical NMO velocity model derived. The method is extremely powerful but relies on high fold of coverage for each CMP location. In North Canterbury a fold of coverage ≥ 24 is required to allow picking of velocity-depth pairs.

iv) Interactive NMO display

This interactive NMO method allows the effect of varying NMO stacking velocities to be seen in real time on a CMP gather. This means very detailed velocity modelling can be undertaken and allow for the direct observation of the effects of NMO stretch and NMO muting to be seen on the data.

NMO correction

Once the velocity model for the subsurface has been obtained the effect of the geometry on the CMP sorted data can be removed. This stage, if correctly applied, should result in a CMP sort gather where reflection events are horizontal, as the NMO component has been removed. Any deviation from this is the result of incorrect lateral or vertical velocity model, dipping reflectors or incomplete or incorrect static corrections.

Residual Statics

Residual statics is a statistical process that improves the continuity of reflection events by estimating the deviation of each trace in a CMP gather, from the "average" of all the traces within a selected window. The deviation of each trace from the optimum or average for the CMP gather, is a complex result of incorrectly accounted for field statics, timing errors, location errors and equipment errors. The application of residual statics must be carefully undertaken and requires a reasonable amount of reflection energy to be present on the CMP stack, to produce a statistically valid comparison trace. Residual statics should only be used to correct for static errors of similar, or smaller, magnitude relative to the reflection wavelet wavelength. Allowing the residual statics algorithm to shift traces by more than this, can result in the generation of unreal reflection type events as the algorithm shifts energy to align random noise to form horizontally continuous non-real events.

Stacking

This process collapses the NMO corrected, CMP-sorted raypaths passing through each subsurface location, into a simulated, zero-offset "super" trace, containing the addition of all energy passing though that subsurface position. The process increases the S/N ratio of the reflection energy which should add constructively, while the noise will be randomly distributed and will not add constructively.

Migration

Migration of a stacked section moves all reflectors and diffractors to their correct lateral and vertical position. Migration is the inverse of seismic forward modelling.

Depth conversion

Conversion of two-way times, in the migrated section, to real depths can now be applied. Using an interval velocity derived from velocity analysis, a laterally and vertically variable velocity model can be defined. This model can then be applied to the migrated, two-way time section to produce a depth converted, stacked and migrated section. This stage is often not applied in a formal way for shallow seismic as the velocity models for the subsurface derived from NMO velocity analysis may be laterally and vertical sparse and limited due to limited reflector packages. The near surface velocities below the vadose zone may also be relatively constant. For these reasons a simple, linearly increasing, velocity model is often assumed and depths calculated for features of interest rather than the conversion of the whole two-way time section to depth.

Interpretation:

Interpretation is the conversion of the seismic section, which is an image of the acoustic boundaries in the subsurface, into a geologic model. The interpretation must be controlled by further information as the seismic section is non-unique and many geologic models can be generated to provide a match. The following factors control the interpretation of the seismic section:

- existing geologic models and known structural geometries and styles in the area
- topography
- seismic interpretation methologies developed over an extended period, that allow seismic character to be directly associated with geologic processes and features
- outcrop geology/geomorphology
- borehole geology
- other geophysical techniques; and
- previous seismic lines that tie-in with the seismic line to be interpreted.

General notes and concluding remarks

Each survey in a different geographical location should be treated as a new survey and the acquisition parameters should be chosen for that unique location. A suggested flow of activities for areas in Canterbury is shown in Figure A6.10. The following results have been established in North Canterbury for obtaining the highest quality shallow p-wave seismic reflection data.

Coupling (Best-Worst)

1. Buried geophone arrays >0.5m.
2. Covered geophone arrays >0.1m.
3. Well planted geophones in moist, well-compacted soil/clay/sand.
4. Well planted geophones in compacted, soil/clay/sand (e.g. next to road).
5. Poorly planted geophone in compacted soil/clay/sand.
6. Geophones in un-compacted, unsaturated soil/gravel (e.g. dry riverbed).

Source (Best-Worst)

1. Hammer and plate on very well compacted surface such as a gravel road (multiple stacks).
2. Seismic gun in deep hole, in well compacted, partly saturated to saturated material (single shot).
3. Hammer and plate on compacted surface, in shallow (<10 cm) hole (e.g. grazing farmland), multiple stack.
4. Seismic gun fired in very shallow hole (<10 cm).
5. Mini-Sosie ™ on well compacted material.
6. Mini-Sosie ™ on un-compacted surface.

Future developments:

Seismic surveying in North Canterbury undertaken for this thesis has used established, commercially available equipment where possible. The methods used and results obtained have been very successful, but are limited by the rate of acquisition and its associated expense. The delineation of small scale, active tectonic and hydrologic features, requires multiple parallel two-dimensional lines or three-dimensional surveying techniques. The main controlling factors in acquisition rates are geophone placement and source operation. Automation of these would greatly increase the usefulness of seismic profiling.

A new geophone placement method using a towed array or land streamer has recently been developed by van der Veen (2001). The method involves pulling an array of geophones and a source across the surface to be imaged. The relative source-receiver geometry remains constant, and by shooting at set intervals a similar subsurface coverage to normal seismic reflection surveying can be obtained. An initial trial of a towed array system has been undertaken in North Canterbury and appears to offer a rapid and useful method for data collection. The system differs from previous towed array systems in the details of its construction, which is based on non-gimballed 40 Hz geophone elements encased in a 5 kg concrete matrix. The design allows an economically viable and mechanically robust towed array to be constructed, which is tailored for the flat gravel roads and fields of the Canterbury Plains (Figure A6.11). Initial surveying indicates acquisition rates of two to three times conventional methods, but is limited by the use of manual sources such as the hammer and plate. Testing indicates that maximum acquisition rates for a towed array require an automated source system such as an accelerated weight drop or mini vibrator.

The shot gather wave field contains a great deal more information than the P-wave component. Within the wave field is shear wave information from s-wave reflections, ground roll and dispersive waves and refraction information. P-wave reflection seismology is only using a small fraction of the available information. Multi component acquisition (P and S wave) acquisition and processing methods, which use a larger component of the whole wave field, would allow a far greater amount of information to be derived about the subsurface (Pullan et al., 1990; Miller et al., 1993).

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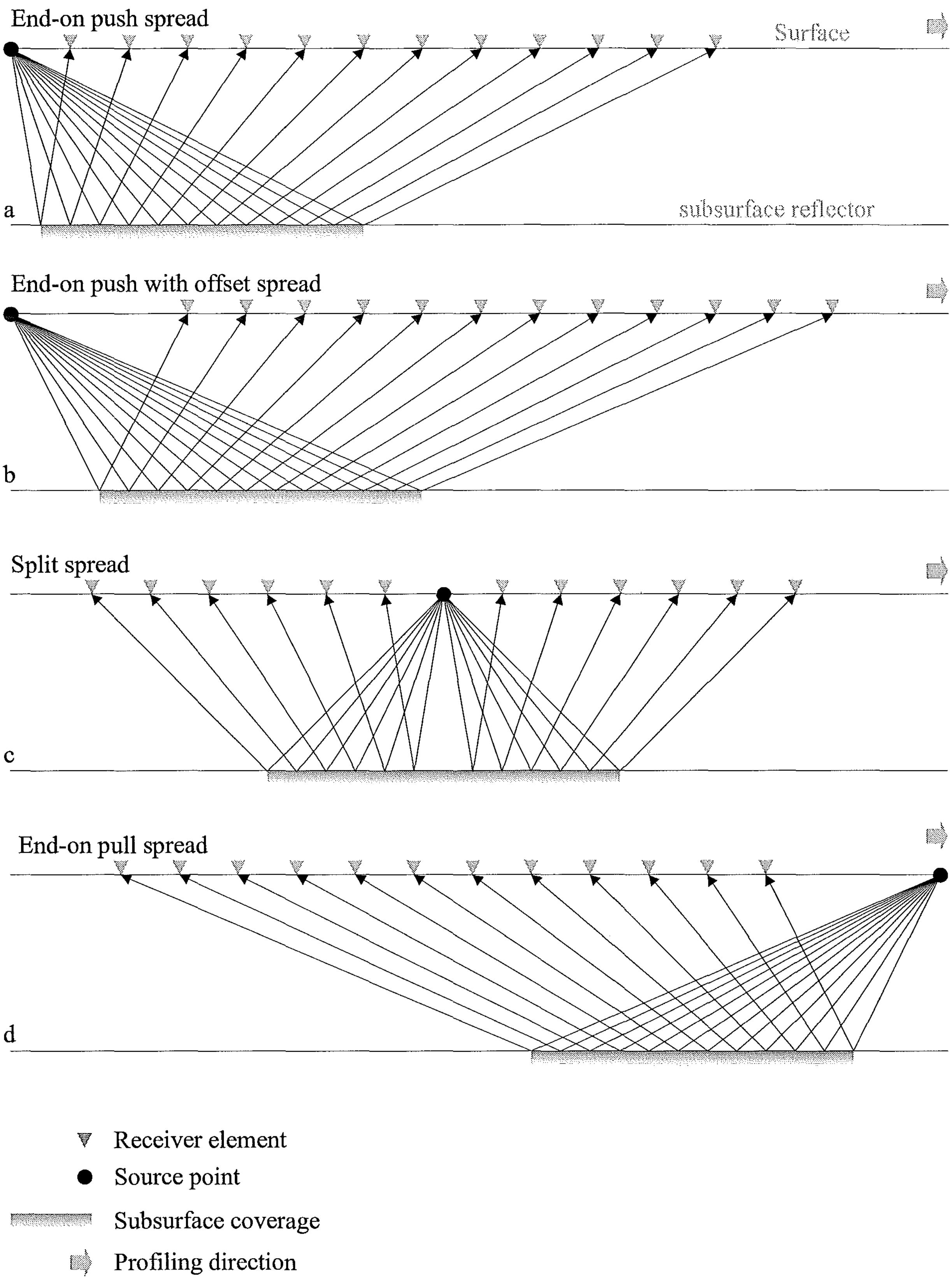


Figure A6.1(a-d) Standard shallow seismic source-receiver geometries.

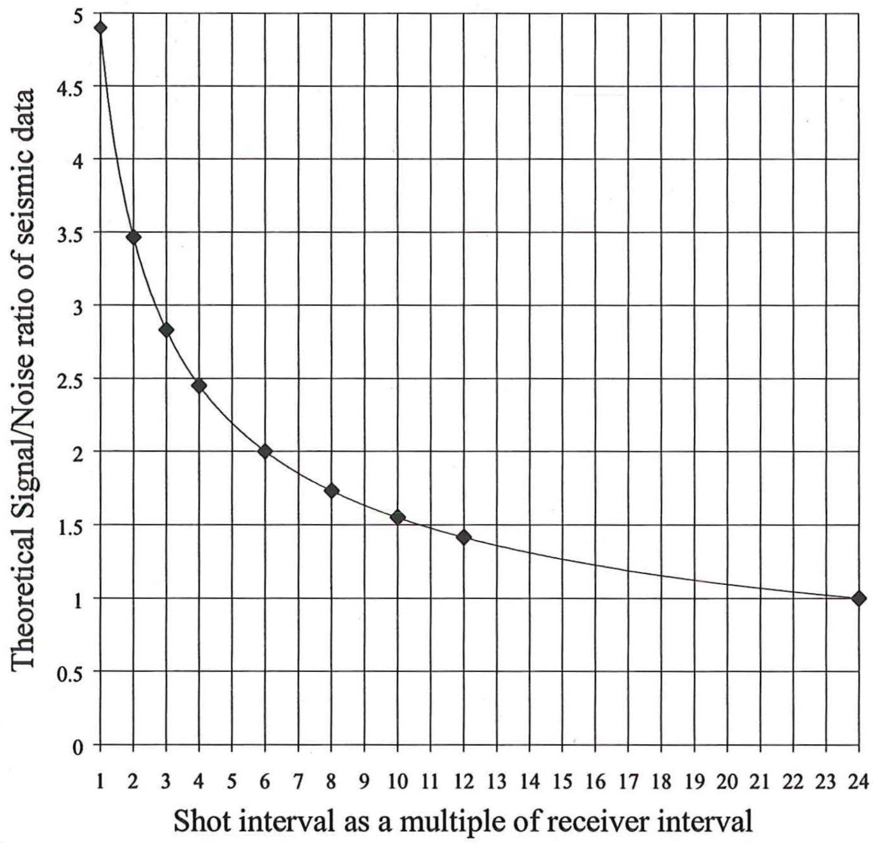


Figure A6.2 The effect of increasing shot point interval on the Signal/Noise ratio of the final processed seismic profile.

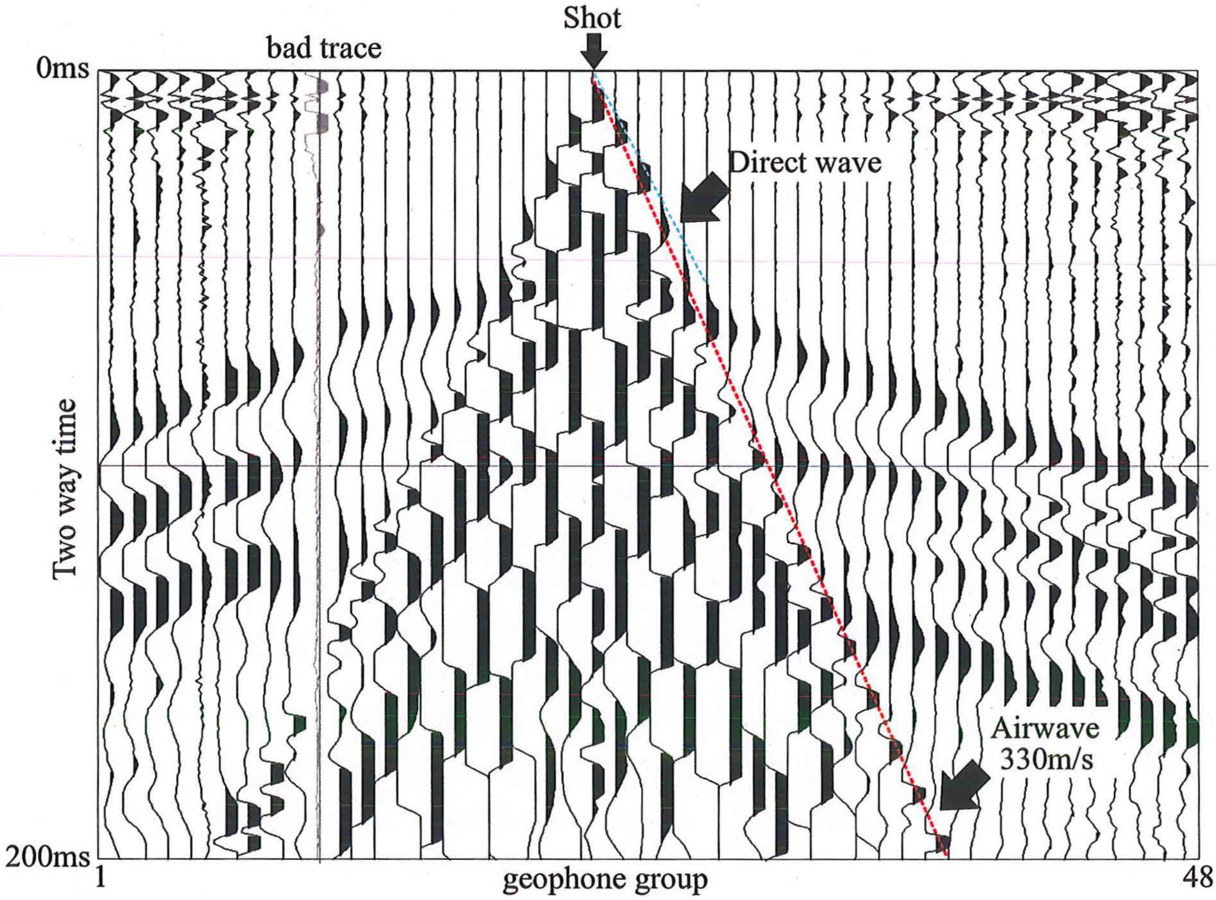
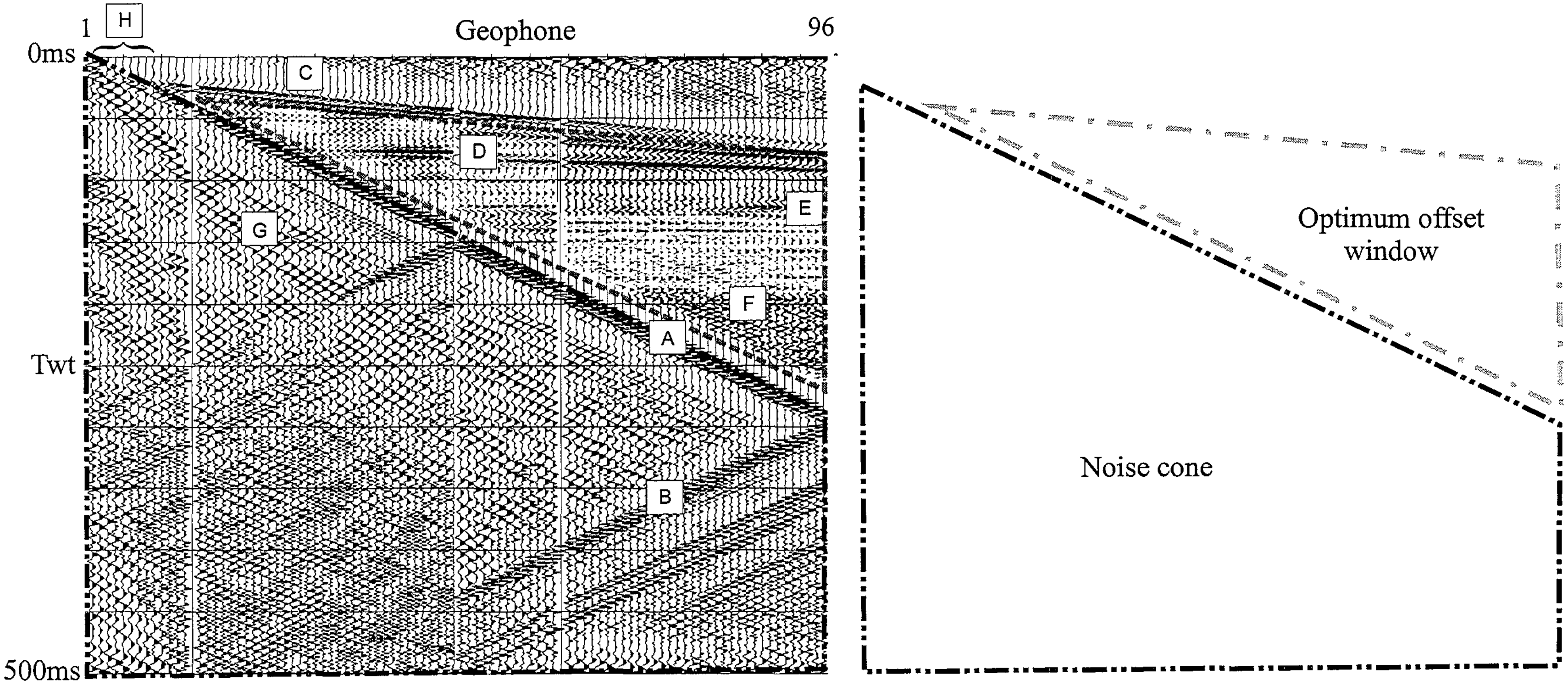


Figure A6.3 Diagram showing a shot gather with airwave, direct wave and shot location. Applied shot location and apex of noise cone should be the same for all shots.



KEY

A: Air-blast (velocity 330m/s).
B: Air-blast echo. The air-blast has been reflected from a nearby shed.
C: Refractions.
D: Strong reflection event.
E: Deepest reflection event. It appears to be a real reflection, but care must be taken not to interpret multiple reflections within the stratigraphy as deeper real events.
F: Possible deeper reflections, may contain further reflection events that would be enhanced in CMP reflection surveying, but are not present in the walkaway test.
G: Ground-roll energy.
H: Shot cone swamping all refraction and reflection energy (X_{min}).

Figure A6.4 Example of frequency filtered shot gather from a walkaway test at Omihi, North Canterbury.

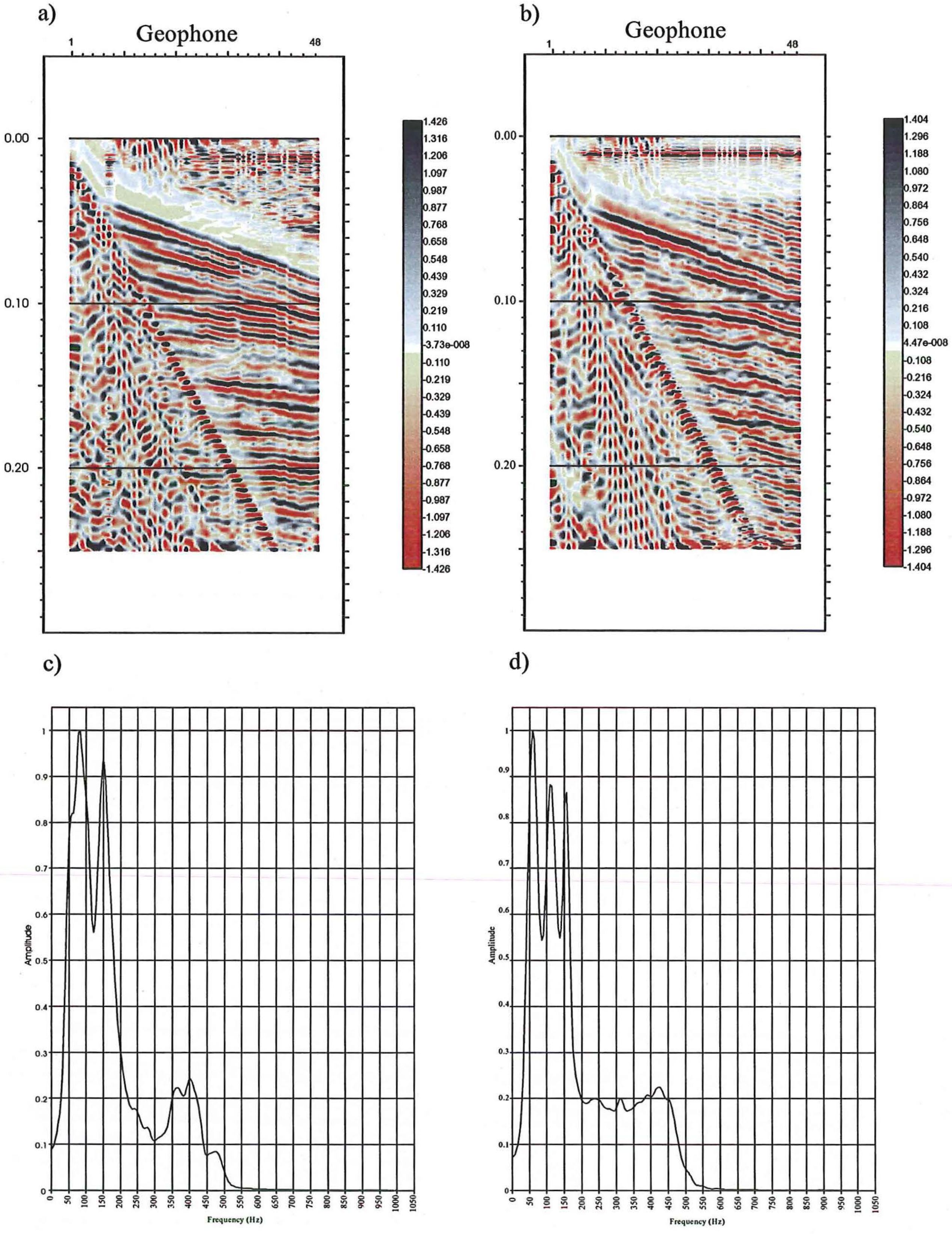


Figure A6.5 Comparison between hammer and plate and seismic pipe gun frequency content for the same survey. a) Shot gather using seismic pipe gun source. b) Shot gather using hammer and plate source. c) Frequency spectrum for seismic gun source d)Frequency spectrum for hammer and plate source.

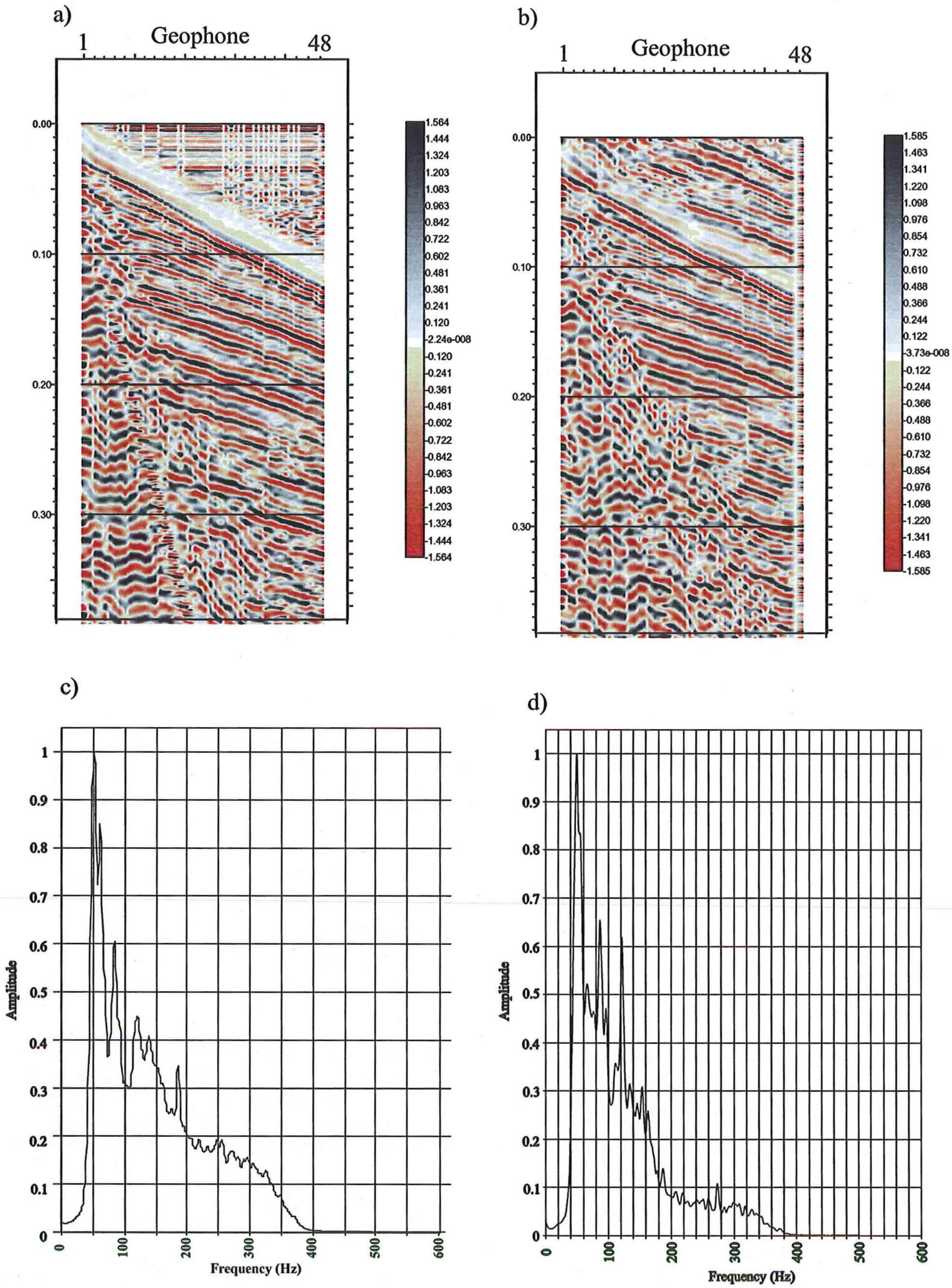


Figure A6.6 Comparison between hammer and plate and mini-sosie frequency content for the same survey. a) Shot gather using hammer and plate. b) Shot gather using mini-sosie system. c) Frequency spectrum for hammer and plate source. d)Frequency spectrum for mini-sosie system. Note: Figure A6.5 and Figure A.6 is data from two different geographic locations.

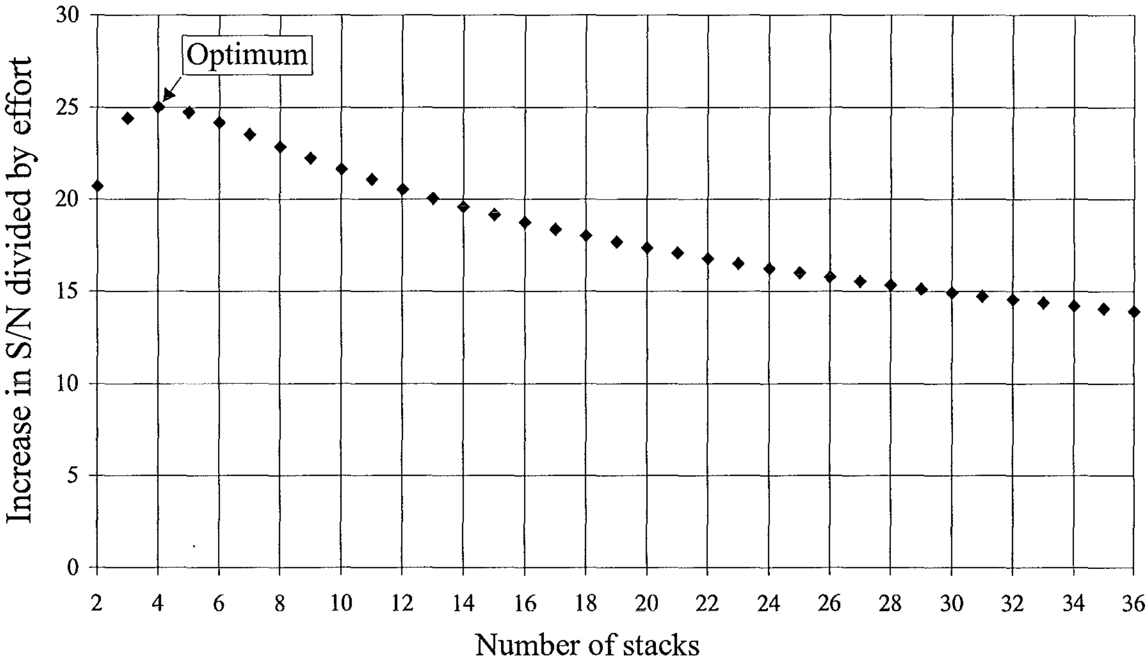


Figure A6.7 Effect of increasing stacks on signal to noise ratio of the reflected signal for a hammer and plate survey.

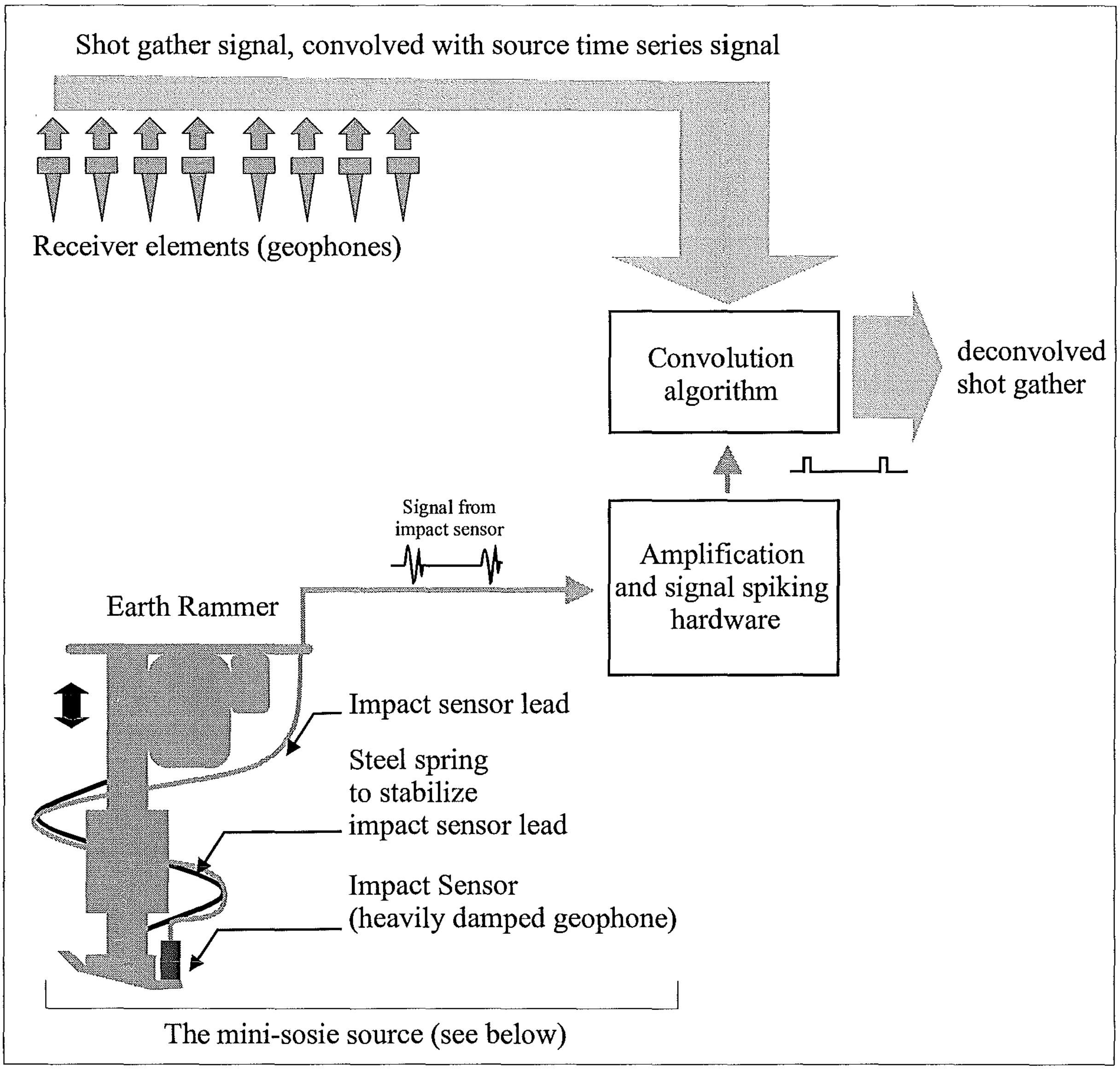


Figure A6.8 The mini-sosie seismic source.

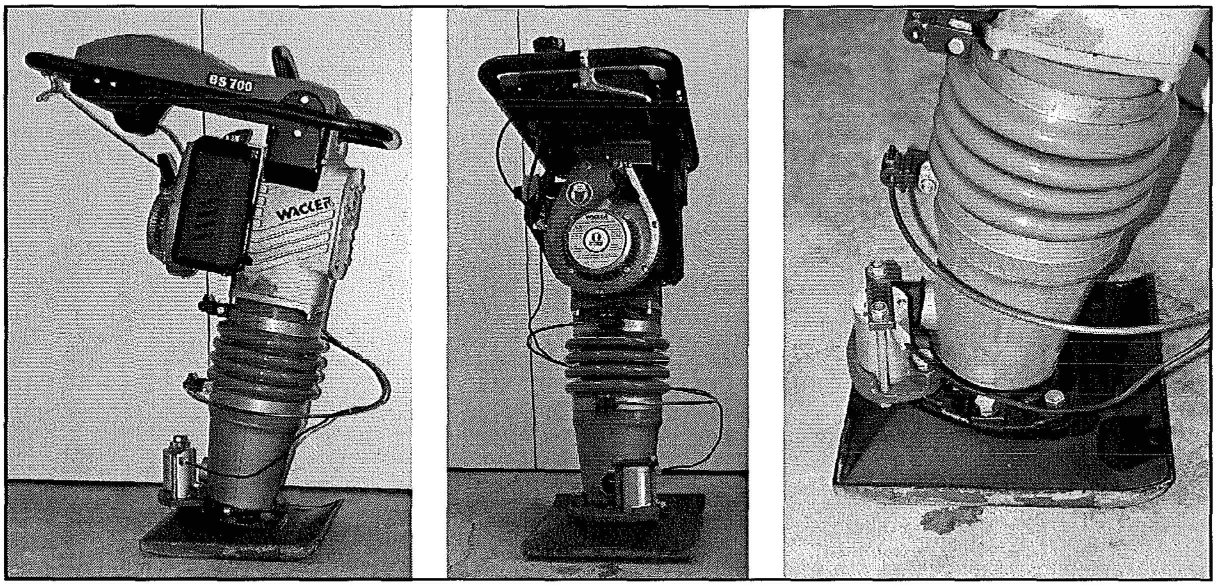


Figure A6.9 Earth rammer, mini-sosie source showing impact sensor and steel spring used to stabilise impact sensor lead and reduce cable vibration.

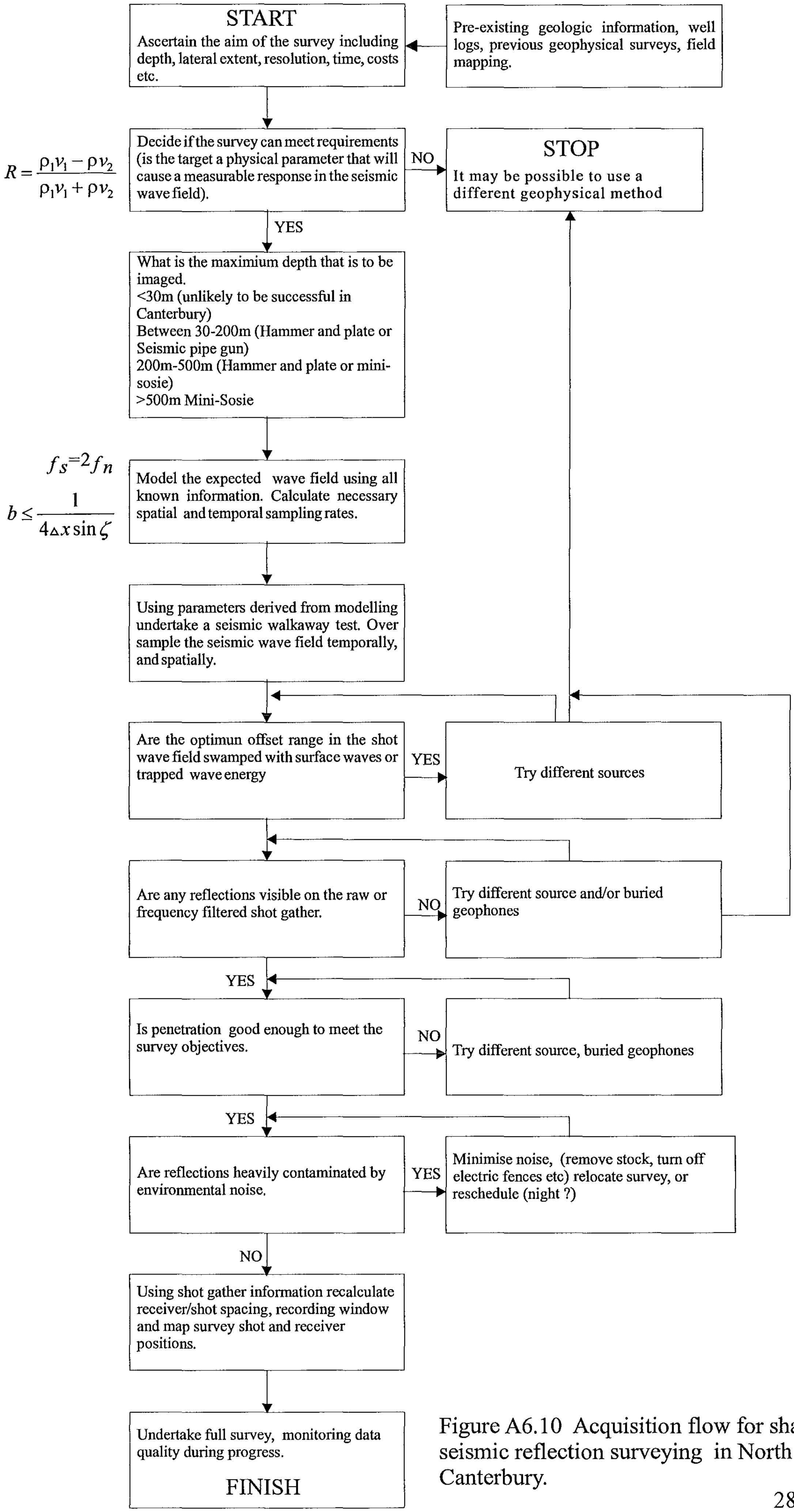


Figure A6.10 Acquisition flow for shallow seismic reflection surveying in North Canterbury.

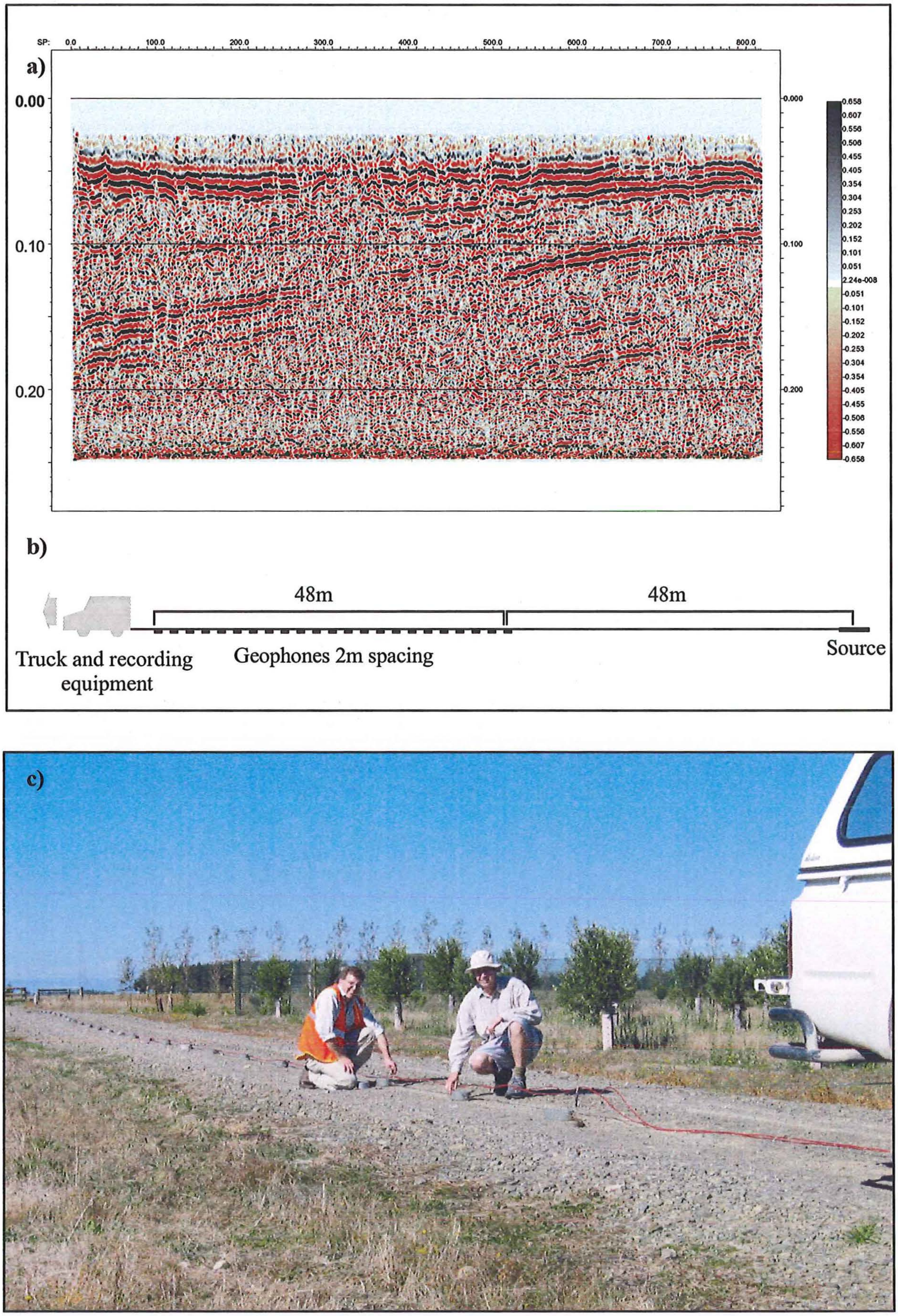


Figure A6.11a-c An initial test of the low cost towed array system developed for the Canterbury Plain conditions. a) Stacked unmigrated seismic section along gravel road at Waipara North Canterbury b) Aquisition geometry diagram c) Photograph of towed array and operators.

Appendix 7

Borehole sampling

Introduction:

During the period 1999-2002 three water wells were logged in the research areas in North Canterbury, two in Omihi Valley (N34-0144, N34-0150) and one at Racecourse Hill (L35-0742). All drilling of the 12" (30 cm) diameter wells was undertaken using the air rotary method by the McMillan Drilling Company Ltd (Brown, 1990). Samples were collected at regular intervals as drilling progressed, and drill tailings were fully described during drilling. The recovered drill samples were later analysed to delineate a ternary grain size distribution of the sediments (gravel/sand and fine grained mud/silt/clay) and to cross check the field descriptions (Lewis, 1983). The samples were also cleaned and photographed.

Field sample collection:

Field samples were collected using a large collection bucket at the drill rig exit manifold (Figure A7.1). The material collected is therefore a mixture of sediment, groundwater, introduced drilling fluid (water + detergent) and high pressure air. The drill sample is also a composite of sediment recovered over several tens of centimetres due to the drilling speed and uneven evacuation of the drill pipe. This recovered material is broken into pieces small enough to exit through the drill bit-casing gap (< 10 cm). The effect of the drilling method on the grain size distribution that is recovered is not fully understood, but the drill rig is believed to recover most of the sediment that it penetrates. It is possible that the pneumatic flow tends to push the small grain sizes into the surrounding pore spaces. This would have the effect of reducing the small grain size component of any recovered material. The rotary drilling action of the drill bit and toothed casing also generates an unknown component of drilling powder as larger clasts are broken down into sub-5 cm fragments. Simple field testing of the effect of smashing Torlesse and limestone clasts indicates that this component is minor and that <5% of the mass of clasts is converted into sand or smaller particles. The material collected from the drill rig outlet manifold is therefore a representative sample of the pre-drilling grain size distribution with the larger clasts broken down into a 0-5 cm clast range. The material was collected over several minutes and a representative 0.5 kg sample was obtained (Lewis, 1983). Samples were taken at regular intervals and/or when changes in colour, texture, grain size distribution or water content were observed. The numbering system used for all samples is CCC-CCC #XX, where CCC-CCC is the ECan well number, and #XX is the sample number.

Laboratory Grain Size Analysis:

Each sample was dried for 72 hours in an oven at 50°C. The samples were then weighed to obtain the dry sample weight and then wet sieved through a four micron (ϕ) sieve to remove the clay and silt component. The sand and gravel component remaining was then dried for a further 72 hours and dry sieved to remove any remaining silt and clay. The remaining material was then weighed and dry sieved using an auto-seive for three minutes though a –2 ϕ sieve to separate the sand component of the sample. The sand component and the pebble and greater size components were then separately weighed.

The silt/clay component was calculated using:

Sample dry weight – dry weight after wet/dry sieving through a 4 ϕ sieve

The gravel component was calculated using:

Dry weight of the material collected in the –1 ϕ sieve

And the sand component was calculated as:

The remaining material that passed though the –1 ϕ sieve

The results give the percentage by weight of the three principal components of the sediment sample. Assuming that the different components have similar densities, the result is the percentage by volume. The auto-sieve was run for a set period of three minutes to separate the sand-size grains from the pebble size and greater, but it was noted that longer shaking periods gave improved sorting and this appeared to continue for very long shaking periods (>10 minutes). This is due to the random nature of the grains and the random alignment with the sieve mesh during shaking. However, the shaking time was kept constant (3 minutes) for all samples and any introduced error would be small and constant. The grain size analysis results for borehole N34-144 and N34-150 are shown in Tables A7.1 and A7.2. Grainsize analysis was not carried on samples from the Racecourse Hill L35-0742 borehole.

Photographic Log:

For all samples the components were recombined (except the silt/clay component, which had been removed) and photographed producing a visual record (Figures A7.2-A7.4).

Remarks:

The grainsize analyses for individual samples are likely to have a large inherent error due to the limitations in the field sampling method. The individual percentage is likely to be at least +/- 20% and should not be used to derive very rapid stratigraphic sediment changes. The log should be used to show more gradual grainsize variations and the values averaged over several readings (Figure A7.5a and A7.5b).

The photographic log is mainly useful in showing the colour changes present. Colour is related to the lithologic composition but is also very strongly dependent on the weathering that the clasts have undergone. The Torlesse clasts are mainly quartzo-feldspathic arenites and argillites. Chemical weathering of the Torlesse gravel is the chemical incongruent dissolution of the quartzo-feldspathic arenites and argillites into a variety of clay minerals. The weathering colour change in Torlesse clasts is caused by the chemical weathering of the feldspars (McSaveney, 1992):

$$SiO_2 + \textit{Aluminosilicates of potassium} + \textit{water} = \textit{Variety of Clay minerals} + H_4SiO_4 + K$$

The weathered clasts tend to develop a distinctive coloured rind. The colour and texture of this rind is dependent on the burial or surface exposure history of the clast. Unburied clasts tend to have a red outer layer, grading inward to white and then an unweathered dark grey core. Buried clasts tend to be red/brown in colour but have a more friable granular surface texture. The darkness of this weathered layer has been shown in several boreholes to indicate increasing age (Brown, 1998). The actual relationship between weathering rind formation and age of deposition has only been delineated for surface rind formation. A similar trend is expected for subsurface clasts but the effect of groundwater is expected to be the major weathering mechanism as well as biogenic effects such as plants that produce corrosive organic acids. For the logged boreholes, the only relationship that is derived for the colour change of the Torlesse clasts is that darker colouration indicates greater weathering and therefore greater age.

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McSaveney, M. J., 1992: A manual for weathering rind dating of grey sandstones of the Torlesse Supergroup New Zealand: Institute of Geological and Nuclear Sciences, Report 92/4, 52 p.

Figure A7.1 Photograph showing collection of borehole samples from borehole N34-0144. Photograph is courtesy of J.Pettinga.

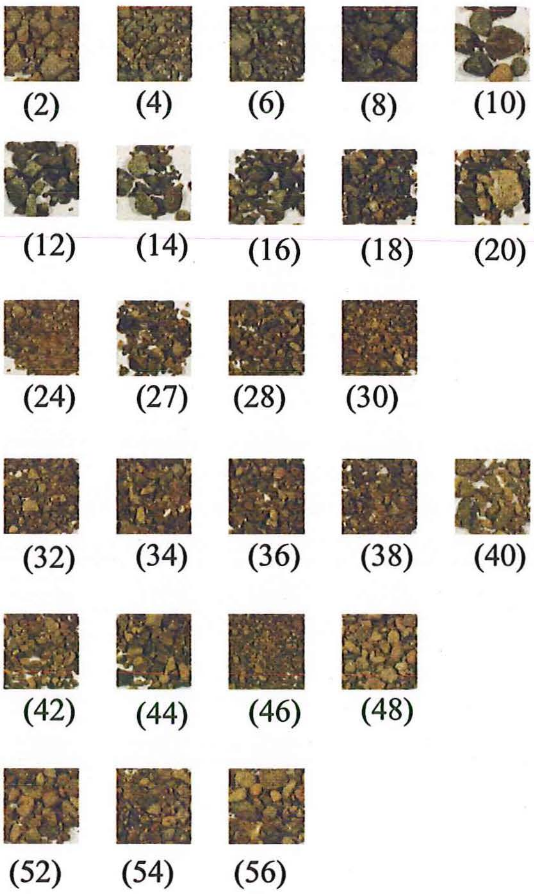

Figure A7.2: L35-742 borehole sample photographs.

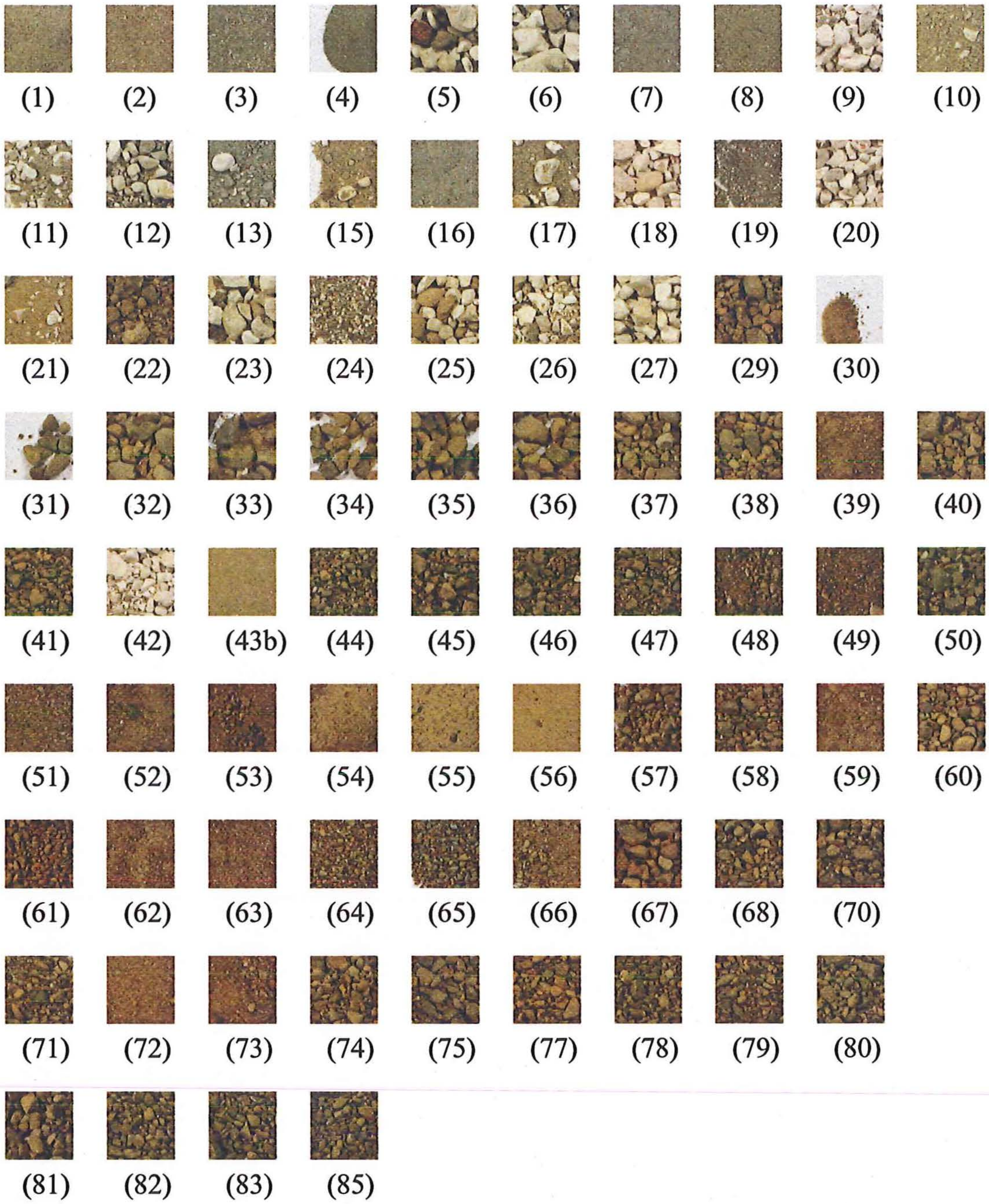

Figure A7.3: N34-144 borehole sample photographs. Samples 1-85 (0-200 m depth).

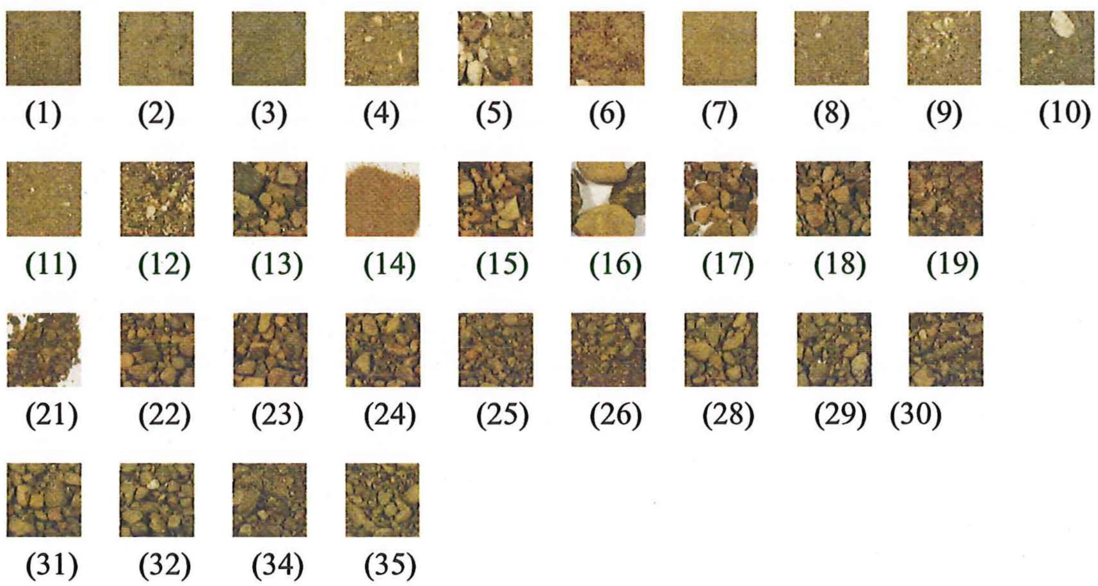

Figure A7.4: N34/0150 borehole sample photographs. Samples 1-35 (0-130 m depth).

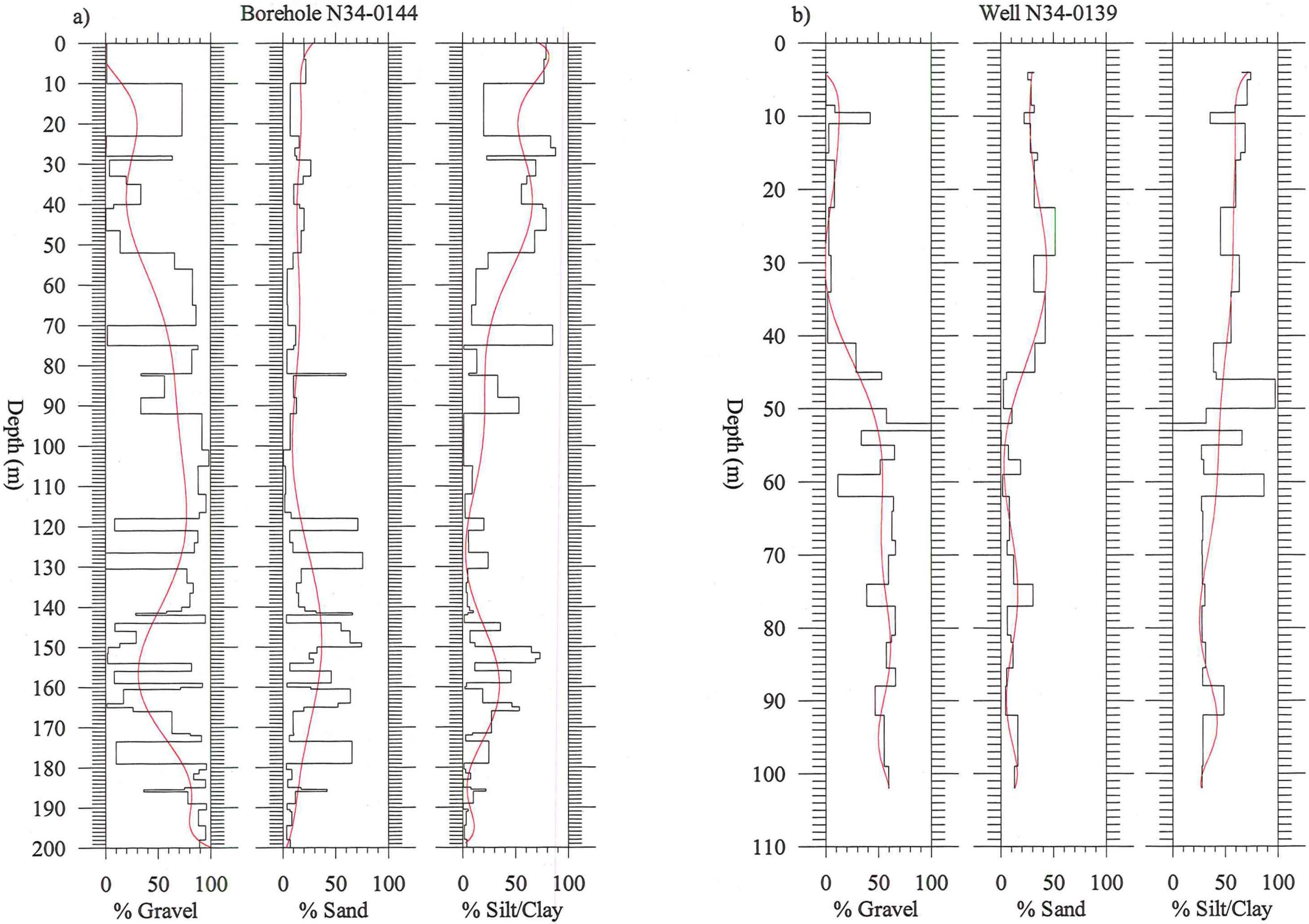

Figure A7.5 a) Grain size analysis for Borehole N34-0144 b) Grain size analysis for well N34-0139.
The red line shows a tenth order polynomial best fit of the data.

N34/0144 Borehole Grain Size Analysis

Sample No.	Depth (m)	Dry Sample+Container (g)	Container1 Weight (g)	Container 2 Weight (g)	Dry Weight before filter (g)	Container +Gravel (g)	Container+Sand/Silt (g)	Gravel (g)	Sand/Silt (g)	Clay (g)	% Gravel	% Sand	% Clay
1	0	526.04	155.02	155.02	371.02	158.02	256.92	3	101.9	266.12	0.8	27.5	71.7
2	4	352.17	155.02	155.02	197.15	156.98	194.67	1.96	39.7	155.54	1.0	20.1	78.9
3	10	328.31	155.02	155.02	173.29	156.98	192.88	1.96	37.9	133.47	1.1	21.8	77.0
4	*16*	*181.73*	*155.02*	*155.02*	*26.71*	*155.02*	*170.59*	*0*	*15.6*	*11.14*	*0.0*	*58.3*	*41.7*
6	23	478.81	155.02	155.02	323.79	391.61	177.76	236.59	22.7	64.46	73.1	7.0	19.9
7	26	537.76	155.02	155.02	382.74	158.3	214.96	3.28	59.9	319.52	0.9	15.7	83.5
8	28	589.71	155.02	155.02	434.69	156.63	205.24	1.61	50.2	382.86	0.4	11.6	88.1
9	29	577.02	155.02	155.02	422	424.05	211.13	269.03	56.1	96.86	63.8	13.3	23.0
10	33	303.65	155.02	155.02	148.63	160.75	194.76	5.73	39.7	103.16	3.9	26.7	69.4
11	35	489.61	155.02	155.02	334.59	221.18	219.9	66.16	64.9	203.55	19.8	19.4	60.8
12	40	512.8	155.02	155.02	357.78	275.89	192.32	120.87	37.3	199.61	33.8	10.4	55.8
13	41	575.95	155.02	155.02	420.93	188.48	222.85	33.46	67.8	319.64	7.9	16.1	75.9
15	*43*	*182.71*	*155.02*	*155.02*	*27.69*	*159.53*	*163.79*	*4.51*	*8.8*	*14.41*	*16.3*	*31.7*	*52.0*
16	46.5	515.05	155.02	155.02	360.03	156.35	228.24	1.33	73.2	285.48	0.4	20.3	79.3
17	52	293.5	155.02	155.02	138.48	174.45	179.42	19.43	24.4	94.65	14.0	17.6	68.3
18	56	375.67	155.02	155.02	220.65	300.2	176.8	145.18	21.8	53.69	65.8	9.9	24.3
19	65	576.42	155.02	155.02	421.4	504.88	173.27	349.86	18.3	53.29	83.0	4.3	12.6
20	70	596.08	155.02	155.02	441.06	536.2	176.91	381.18	21.9	37.99	86.4	5.0	8.6
21	75	490.63	155.02	155.02	335.61	161.66	197.1	6.64	42.1	286.89	2.0	12.5	85.5
22	76	584.93	155.02	155.02	429.91	534.8	200.42	379.78	45.4	4.73	88.3	10.6	1.1
23	82	601.04	155.02	155.02	446.02	522.04	173.77	367.02	18.8	60.25	82.3	4.2	13.5
24	82.5	491.33	155.02	155.02	336.31	268.92	357.6	113.9	202.6	19.83	33.9	60.2	5.9
25	88	566.58	155.02	155.02	411.56	386.91	197.57	231.89	42.6	137.12	56.3	10.3	33.3
26	92	429.33	155.02	155.02	274.31	247.34	190.74	92.32	35.7	146.27	33.7	13.0	53.3
29	101	566.09	155.02	155.02	411.07	533.14	184.25	378.12	29.2	3.72	92.0	7.1	0.9
30	*103*	*159.34*	*155.02*	*155.02*	*4.32*	*155.22*	*156.12*	*0.2*	*1.1*	*3.02*	*4.6*	*25.5*	*69.9*
31	*104*	*170.84*	*155.02*	*155.02*	*15.82*	*170.6*	*155.16*	*15.58*	*0.1*	*0.10*	*98.5*	*0.9*	*0.6*
32	105	480.87	155.02	155.02	325.85	475.72	157.23	320.7	2.2	2.94	98.4	0.7	0.9
33	106	328.2	155.02	155.02	173.18	307.39	159.42	152.37	4.4	16.41	88.0	2.5	9.5
34	*109*	*196.81*	*155.02*	*155.02*	*41.79*	*196.01*	*155.42*	*40.99*	*0.4*	*0.40*	*98.1*	*1.0*	*1.0*
35	112	335.43	155.02	155.02	180.41	314.12	160.06	159.1	5.0	16.27	88.2	2.8	9.0
36	*116.5*	*234.57*	*155.02*	*155.02*	*79.55*	*231.07*	*156.69*	*76.05*	*1.7*	*1.83*	*95.6*	*2.1*	*2.3*
37	117	338.64	155.02	155.02	183.62	305.28	168.47	150.26	13.5	19.91	81.8	7.3	10.8
38	118	428.32	155.02	155.02	273.3	399.36	177.21	244.34	22.2	6.77	89.4	8.1	2.5
39	121	292.3	155.02	155.02	137.28	166.87	252.9	11.85	97.9	27.55	8.6	71.3	20.1
40	124	536.41	155.02	155.02	381.39	490.64	180.5	335.62	25.5	20.29	88.0	6.7	5.3
41	126.5	525.36	155.02	155.02	370.34	468.63	190.72	313.61	35.7	21.03	84.7	9.6	5.7
43B	130.5	469.15	155.02	155.02	314.13	155.02	392.84	0	237.8	76.31	0.0	75.7	24.3
44	134	525.16	155.02	155.02	370.14	442.34	220.56	287.32	65.5	17.28	77.6	17.7	4.7
45	136.5	577.92	155.02	155.02	422.9	508.07	210.94	353.05	55.9	13.93	83.5	13.2	3.3
46	140	467.52	155.02	155.02	312.5	406.46	202.04	251.44	47.0	14.04	80.5	15.0	4.5
47	141	461.48	155.02	155.02	306.46	377.33	219.18	222.31	64.2	19.99	72.5	20.9	6.5
48	141.5	543.57	155.02	155.02	388.55	381.45	277.75	226.43	122.7	39.39	58.3	31.6	10.1
49	142	417.42	155.02	155.02	262.4	230.8	328.47	75.78	173.5	13.17	28.9	66.1	5.0
50	144	490.9	155.02	155.02	335.88	474.44	166.52	319.42	11.5	4.96	95.1	3.4	1.5
51	146	430.73	155.02	155.02	275.71	179.65	307.23	24.63	152.2	98.87	8.9	55.2	35.9
52	149	498.76	155.02	155.02	343.74	255.7	374.36	100.68	219.3	23.72	29.3	63.8	6.9
53	150	518.53	155.02	155.02	363.51	204.96	426.51	49.94	271.5	42.08	13.7	74.7	11.6
54	151.5	355.75	155.02	155.02	200.73	160.04	220.13	5.02	65.1	130.60	2.5	32.4	65.1
55	153	472.35	155.02	155.02	317.33	160.89	234.49	5.87	79.5	231.99	1.8	25.0	73.1
56	154	286	155.02	155.02	130.98	157.6	193.2	2.58	38.2	90.22	2.0	29.1	68.9
57	156	272.51	155.02	155.02	117.49	251.24	162.91	96.22	7.9	13.38	81.9	6.7	11.4
58	*157.5*	*234.38*	*155.02*	*155.02*	*79.36*	*216.09*	*166.8*	*61.07*	*11.8*	*6.51*	*77.0*	*14.8*	*8.2*
59	159	402.36	155.02	155.02	247.34	175.67	268.45	20.65	113.4	113.26	8.3	45.9	45.8
60	160	484.26	155.02	155.02	329.24	459.2	168.19	304.18	13.2	11.89	92.4	4.0	3.6
61	160.5	546.82	155.02	155.02	391.8	435.09	258.5	280.07	103.5	8.25	71.5	26.4	2.1
62	164	394.37	155.02	155.02	239.35	196.05	308.19	41.03	153.2	45.15	17.1	64.0	18.9
63	165	256.24	155.02	155.02	101.22	156.04	208	1.02	53.0	47.22	1.0	52.3	46.7
64	166	458.03	155.02	155.02	303.01	234.66	215.57	79.64	60.6	162.82	26.3	20.0	53.7
65	*170*	*245.31*	*155.02*	*155.02*	*90.29*	*208.94*	*168.59*	*53.92*	*13.6*	*22.80*	*59.7*	*15.0*	*25.3*
66	*171*	*188.4*	*155.02*	*155.02*	*33.38*	*159.59*	*163.48*	*4.57*	*8.5*	*20.35*	*13.7*	*25.3*	*61.0*
67	171.5	552.1	91.97	91.97	460.13	382.75	136.53	290.78	44.6	124.79	63.2	9.7	27.1
68	172	601.38	91.97	91.97	509.41	502.54	144.17	410.57	52.2	46.64	80.6	10.2	9.2
69	173.5	226.37	91.97	155.02	134.4	277.76	163.09	122.74	8.1	3.59	91.3	6.0	2.7
72	179	230.33	91.97	155.02	138.36	168.85	245.54	13.83	90.5	34.01	10.0	65.4	24.6
73	*180*	*183.78*	*91.97*	*91.97*	*91.81*	*112.54*	*144.76*	*20.57*	*52.8*	*18.45*	*22.4*	*57.5*	*20.1*
74	180.5	570.1	155.02	155.02	415.08	552.85	168.68	397.83	13.7	3.59	95.8	3.3	0.9
75	181.5	591.78	91.97	155.02	499.81	599.58	196.89	444.56	41.9	13.38	88.9	8.4	2.7
76	183	506.31	155.02	155.02	351.29	449.7	185.74	294.68	30.7	25.89	83.9	8.7	7.4
77	185	595.69	91.97	91.97	503.72	571.28	115.38	479.31	23.4	1.00	95.2	4.6	0.2
78	185.5	605.65	91.97	91.97	513.68	477.71	180.23	385.74	88.3	39.68	75.1	17.2	7.7
79	186	598.37	91.97	155.02	506.4	338.54	367.07	183.52	212.1	110.83	36.2	41.9	21.9
80	189	590.39	91.97	91.97	498.42	482	150.52	390.03	58.6	49.84	78.3	11.7	10.0
81	190.5	559.66	91.97	155.02	467.69	603.51	173.29	448.49	18.3	0.93	95.9	3.9	0.2
82	191	605.82	155.02	155.02	450.8	553.3	184.97	398.28	30.0	22.57	88.3	6.6	5.0
83	194.5	606.13	91.97	91.97	514.16	546.46	135.46	454.49	43.5	16.18	88.4	8.5	3.1
84	198	567.84	91.97	155.02	475.87	607.15	172.03	452.13	17.0	6.73	95.0	3.6	1.4
85	200	599.35	91.97	155.02	507.38	607.84	190	452.82	35.0	19.58	89.2	6.9	3.9

Samples in Italics are to small to be valid (<100 g of material)

Table A7.1

N34/0150 Borehole Grain Size Analysis

Sample No.	Depth (m)	Dry Sample+Container (g)	Container1 Weight (g)	Container 2 Weight (g)	Dry Weight before filter (g)	Container +Gravel (g)	Container+Sand/Silt (g)	Gravel (g)	Sand/Silt (g)	Clay (g)	% Gravel	% Sand	% Clay
1	4	582.27	155.02	236.66	160.68	230.47	5.66	75.5	345.61	-260.38	2.4	31.9	65.7
2	5	568.85	155.02	209.25	155.73	208.45	0.71	53.4	359.60	5.00	0.3	25.5	74.1
3	8.5	429.75	155.02	219.54	155.71	218.52	0.69	63.5	210.21	8.50	0.3	28.9	70.8
4	9.5	310.73	155.02	261.24	178.17	238	23.15	83.0	49.49	9.50	8.9	31.8	59.4
5	11	570.1	155.02	436.42	339.04	252.38	184.02	97.4	133.68	11.00	42.2	22.3	35.5
6	15	532.19	155.02	226.71	161.91	219	6.89	64.0	305.48	15.00	3.0	28.2	68.7
7	16	595.75	155.02	239.93	156.07	238.88	1.05	83.9	355.82	16.00	0.4	35.0	64.6
8	22.5	570.18	155.02	260.17	176.69	237.85	21.67	82.8	310.01	22.50	8.3	31.8	59.8
9	29	567.19	155.02	341.4	165.3	330.94	10.28	175.9	225.79	29.00	3.0	51.5	45.5
10	34	600.14	155.02	244.72	167.59	232.15	12.57	77.1	355.42	34.00	5.1	31.5	63.3
11	41	607.19	155.02	278.99	160.87	273.16	5.85	118.1	328.20	41.00	2.1	42.3	55.6
12	45	583.44	155.02	399.78	270.49	284.3	115.47	129.3	183.66	45.00	28.9	32.3	38.8
13	46	404.73	155.02	373.87	353.26	175.57	198.24	20.6	30.86	46.00	53.0	5.5	41.5
14	50	172.58	155.02	159.05	155.02	159.05	0	4.0	13.53	50.00	0.0	2.5	97.5
15	52	581.33	155.02	487.42	435.94	206.68	280.92	51.7	93.91	52.00	57.6	10.6	31.8
16	53	Just gravel	155.02				-155.02	-155.0	#VALUE!	53.00	100.0	0.0	0.0
17	55	236.6	155.02	235.14	234.35	155.8	79.33	0.8	1.46	55.00	33.7	0.3	65.9
18	57	600.86	155.02	565.73	524.31	196.56	369.29	41.5	35.13	57.00	65.3	7.3	27.4
19	59	589.06	155.02	525.31	426.47	253.53	271.45	98.5	63.75	59.00	51.7	18.8	29.6
20	59.5						0	0.0	0.00	59.50			
21	62	180.52	155.02	178.57	175.7	157.89	20.68	2.9	1.95	62.00	11.6	1.6	86.8
22	64	602.18	155.02	565.8	519.14	201.63	364.12	46.6	36.38	64.00	64.4	8.2	27.4
23	68	584.42	155.02	541.47	495.3	200.99	340.28	46.0	42.95	68.00	62.8	8.5	28.7
24	70	594.89	155.02	558.94	525.6	188.36	370.58	33.3	35.95	70.00	66.3	6.0	27.7
25	74	585.65	155.02	549.42	482.13	222.25	327.11	67.2	36.23	74.00	59.5	12.2	28.2
26	77	601.81	155.02	507.07	352.06	310.26	197.04	155.2	94.74	77.00	38.9	30.6	30.5
27							0	0.0	0.00				
28	81	588.81	155.02	557.2	522.3	189.99	367.28	35.0	31.61	81.00	65.9	6.3	27.8
29	82	598.8	155.02	551.88	498.81	208.3	343.79	53.3	46.92	82.00	62.3	9.7	28.1
30	85.5	556.61	155.02	499.48	441.68	212.7	286.66	57.7	57.13	85.50	57.4	11.5	31.1
31	88	585.44	155.02	548.99	517.92	185.59	362.9	30.6	36.45	88.00	66.1	5.6	28.3
32	92	329.28	155.02	318.1	303.77	169.3	148.75	14.3	11.18	92.00	46.8	4.5	48.7
33	95		155.02				-155.02	-155.0	0.00	95.00			
34	99	603.56	155.02	542.61	454.87	242.37	299.85	87.4	60.95	99.00	55.3	16.1	28.6
35	102	603.64	155.02	560.55	488.43	226.92	333.41	71.9	43.09	102.00	59.5	12.8	27.7

Table A7.2

Appendix 8

Maps for North Canterbury Surveys

Maps

Map 1 – Topographic map of the North Canterbury Plains showing location of field areas.

Map 2 – Index map of Omihi seismic reflection lines.

Map 3 – Index map of Burnt Hill seismic reflection lines.

Map 4 – Index map of Racecourse Hill seismic reflection lines.

Map 5 – Geology of the Omihi Valley and surrounding area.

See accompanying Box-1